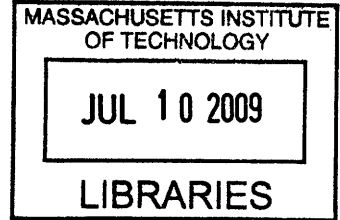# Carbon Impact of Proposed Hydroelectric Dams in Chilean Patagonia

by

Laura E. Mar

B.S., Civil and Environmental Engineering
Cornell University, 2005

Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of
the Requirements for the Degree of

Master of Engineering in Civil and Environmental Engineering
at the
Massachusetts Institute of Technology

June 2009

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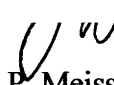hereafter created.

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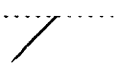
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ABSTRACT

The concern for and awareness of climate change is growing, and the world needs to react quickly and efficiently to manage the carbon intensity of the global energy industry. Making smart decisions about energy technology development requires a methodology to compare alternatives; one such methodology is a greenhouse gas emissions impact assessment.

In the Aysén region of Chilean Patagonia, five hydroelectric dams with a nameplate capacity of 2,750 MW are proposed on the Rio Baker and Rio Pascua. The electricity will be transmitted 2,240 kilometers north to the industrial demand center in the Santiago vicinity. In this analysis, the greenhouse gas impact of the proposed dams is compared to the baseline scenario: developing natural gas power plants near Santiago. Emissions from four categories are calculated: construction, material embedded energy, land-use change, and operations. The main source of available data is published literature, a synthesis of which will serve as the basis for this thesis. Additional information is drawn from local contacts and discussions with local stakeholders. Of the six greenhouse gases, this study will focus on carbon dioxide and methane, reported as carbon dioxide equivalents.

Results show that the natural gas alternative emits 13 times more carbon dioxide than the proposed hydroelectric plants with the high-voltage transmission line. However, the impact of deforestation to build the transmission lines is significant, and less carbon intensive options are likely available.

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ACKNOWLEDGEMENTS

BIOGRAPHY

The author, Laura E. Mar, graduated from Cornell University in 2005 with a Bachelor of Science in Civil and Environmental Engineering. She worked as an environmental engineering consultant for Camp Dresser and McKee for three years before returning to obtain her Master of Engineering degree at MIT. Laura is keenly interested in providing solutions to the global climate crisis, and will continue to pursue her career in greenhouse gas management and sustainable development.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION[1]

Five dams with a nameplate capacity of 2,750 MW are proposed on the Rio Baker and the Rio Pascua in Chilean Patagonia. The power from the proposed dams will be transmitted north through high voltage power lines to address the rising energy demand of Santiago and its surrounding industry, specifically copper mining. Currently, no infrastructure connects the southern and northern electricity grids, therefore a 2,240 km transmission line will be required (Conservacion Patagonica). The proposed transmission line would become the longest transmission line in the world next to the 1,500 km line that connects Quebec to New England (Patagonia without Dams Campaign).

A carbon impact analysis is used to assess the global warming impact of the proposed dams; the carbon emissions are compared to a baseline: the construction of natural gas power near Santiago. The results of the carbon impact analysis are evaluated to determine which solution will contribute the least to global warming.

1.1. Motivation

The Intergovernmental Panel on Climate Change (IPCC) concluded that increases in global average temperatures are "very likely due to the observed increase in anthropogenic greenhouse gas concentrations," and these greenhouse gases are primarily from the burning of fossil fuels (IPCC, 2007). Further, they concluded that emissions must be reduced between 50 to 85% by 2050, if global warming is to be confined between 2.0°C and 2.4°C. Based on the IPCC predictions, the United Nations has adopted a stabilization target of 550 ppm (IPCC, 2007); IPCC scenarios are summarized in Figure 1-1. Low carbon energy production capable of providing inexpensive, reliable, base-load power will be of particular importance if Chile is to develop a low-carbon energy economy, consistent with United Nations goals.

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[1] Components of this section are a result of a group effort between Gianna Leandro, Laura Mar, Kristen Burrall, Elisabetta Natale, and Flavia Tauro.

CO$_2$ emissions and equilibrium temperature increases for a range of stabilisation levels
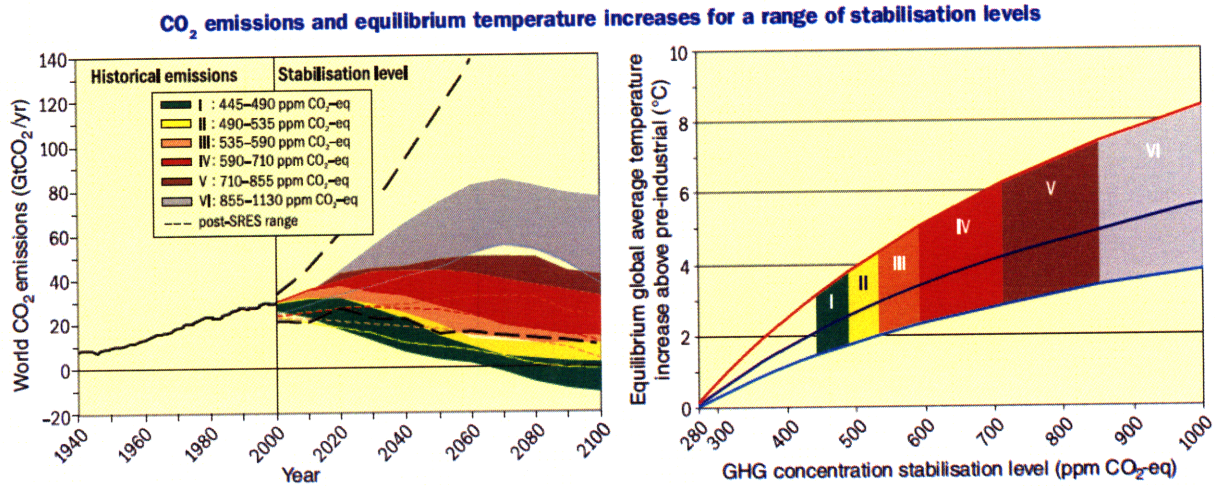
Figure 1-1 Projected growth in CO$_2$: IPCC Stabilization Levels (IPCC, 2007)

Electricity demand has grown steadily in Chile; over the past 20 years Chile's electricity demand has increased 6.7% per year and growth is expected to continue (Universidad de Chile, 2008). Latin America emits roughly 6% of the world's carbon, only 0.2% of global emissions are attributed to Chile (EIA, 2008). However, Chile is like many developing countries, and increased energy consumption has led to rapid growth in greenhouse gas emissions (Figure 1-2). Although Chile's impact on climate change is relatively small, in order to achieve IPCC's 2050 target of 50 to 85% reduction in global emissions, all nations and all projects must consider their contribution. This analysis is intended to set the foundation for energy decisions in Chile for a new low-carbon economy.
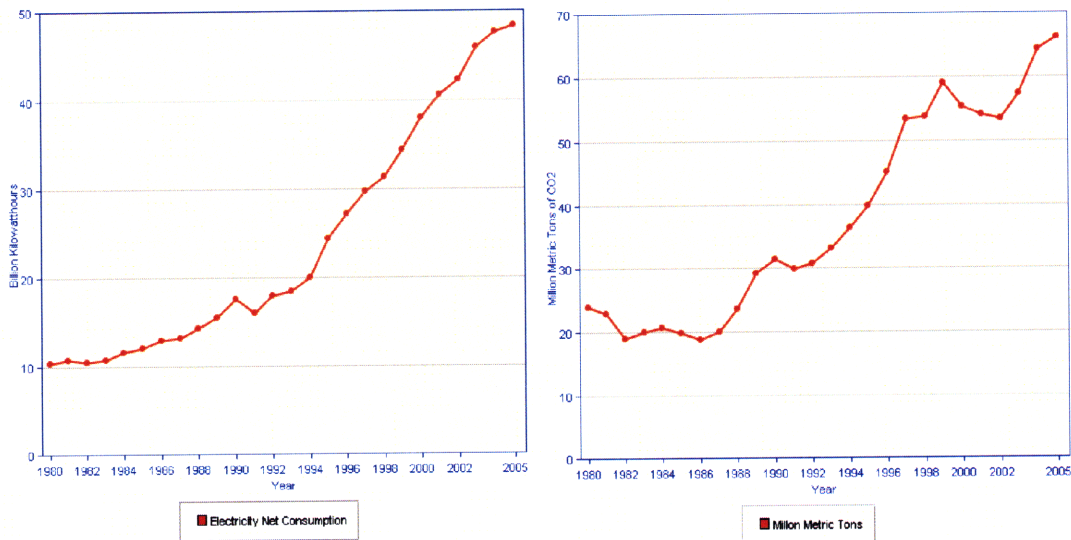
Figure 1-2: Chile's Increasing Electricity Consumption (billion kWh) and Carbon Dioxide Emissions (million metric tons) from 1980 to 2005 (EIA, 2008)

9

1.2. Chile

At the tip of South America, Chile is flanked by Argentina and Bolivia to the East, Peru to the North, and the Pacific Ocean to the West. With a total area of 75.7 million hectares, Chile is approximately twice the size of Montana. Because of its unique geometry spanning from approximately -20° to -56° latitude, Chile's climate varies greatly. Generally temperate, the climate can be characterized as desert in the north, Mediterranean in the central region, and cool and damp in the south (CIA, 2008). Chile's terrain is equally varied with a combination of low coastal mountains, a fertile central valley, and the rugged Andes in the east.

The ten million-hectare Aysén Region (Figure 1-3) is home to the Rio Baker and Rio Pascua, and is Chile's least populous administrative region with approximately 0.9 persons per square kilometer. The Rio Baker originates in Bertrand Lake and empties into the fjords of the Pacific Ocean near the small community of Tortel (Pabich, 2008). The watershed that contains the Rio Baker encompasses a wide variety of habitats from mountain glaciers to river-braided floodplains, and in these varied physical habitats a large array of plant and animal species thrive (Strittholt, 2008).
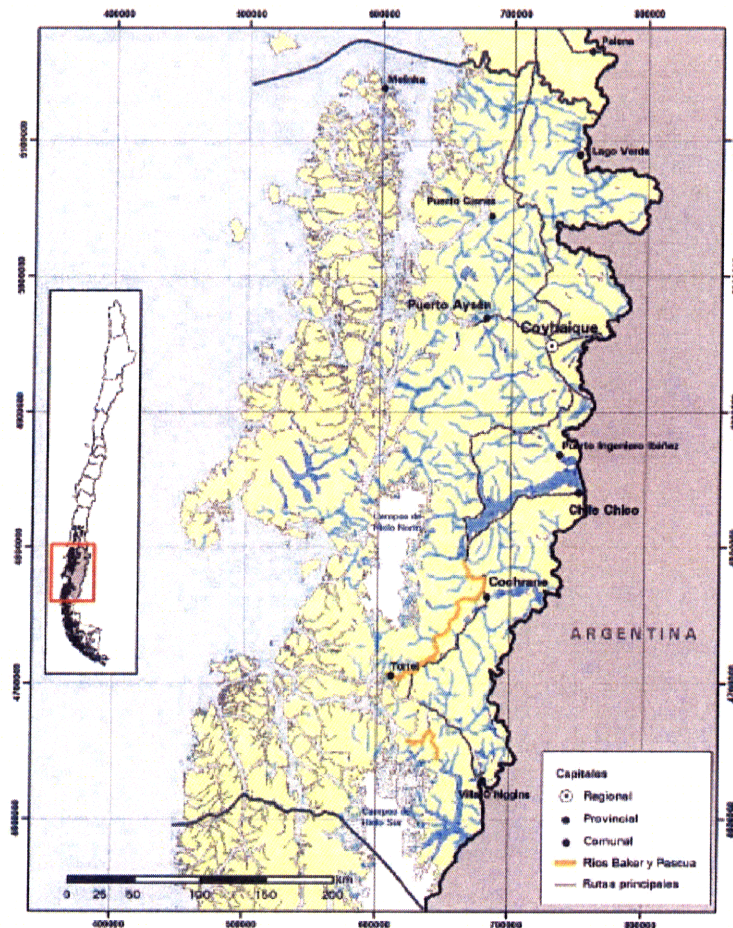
Figure 1-3 Aysén Region of Chile (HidroAysén, 2008)

1.2.1. Energy and Electricity

Chile's energy sector consists primarily of hydropower and natural gas; 40% and 50% generating capacity respectively based on 2000 values (EIA, 2008). However, due to recent concerns about global warming and energy security, Chile is interested in diversifying its energy sector. To date, diversification has been compromised by inadequate policies and regulations, and by unattractive financial incentives for investors (Universidad de Chile, 2008).

Chile has many short rivers that flow west from the Andes to the Pacific Ocean. The majority of rivers are unnavigable due to significant rapids; however, the rivers are an important part of Chile's resources, and are used for both hydropower and irrigation. On these rivers are eleven hydroelectric plants with capacities greater than 100 MW. The largest dam (500 MW) is located on the Biobio River in central Chile (GENI, 2002).

Historically, natural gas was piped through central Chile from Argentina's Neuquén Basin. However, in 2004, Argentina adopted policies that created volatile international natural gas trade; at times, natural gas supply was reduced well below Chilean needs (Wharton, 2007). As a result, Chile was subject to the political will of Argentina for their growing natural gas demands. Reduced and insecure natural gas imports significantly impacted Chile's energy sector and forced Chile to resort to diesel power. Due to this political unrest, the Chilean government is no longer importing any natural gas from Argentina and a liquefied natural gas terminal is being built northwest of Santiago to address the country's energy needs. It is expected that natural gas (as liquefied natural gas) will be imported from Trinidad and Tobago or LNG terminals in Africa such as Egypt, Libya, or Nigeria (Global LNG Limited, 2009; J. Leidich, personal communication, 2009).

In 2007, Chile produced 50,370 GWh of electricity (EIA, 2008). The majority of this electricity (69.6%) was consumed by mining and industry, with copper being the dominant player (Figure 1-4) (Universidad de Chile, 2008). In 2005, Chile produced one-third of the global copper and was the largest copper producer in the world. The global copper industry has been growing exponentially since the 1950's. In 1900, only 0.2 million tonnes of copper was produced annually; production around 2000 was upwards of 15 million tones per year (Wikipedia, 2009c). The growth in the global copper industry has driven the growth in Chilean copper, which in turn has resulted in increased electricity consumption. The Chilean Copper Commission projects 3.5% growth in copper production between 2018 and 2025 (COCHILCO).
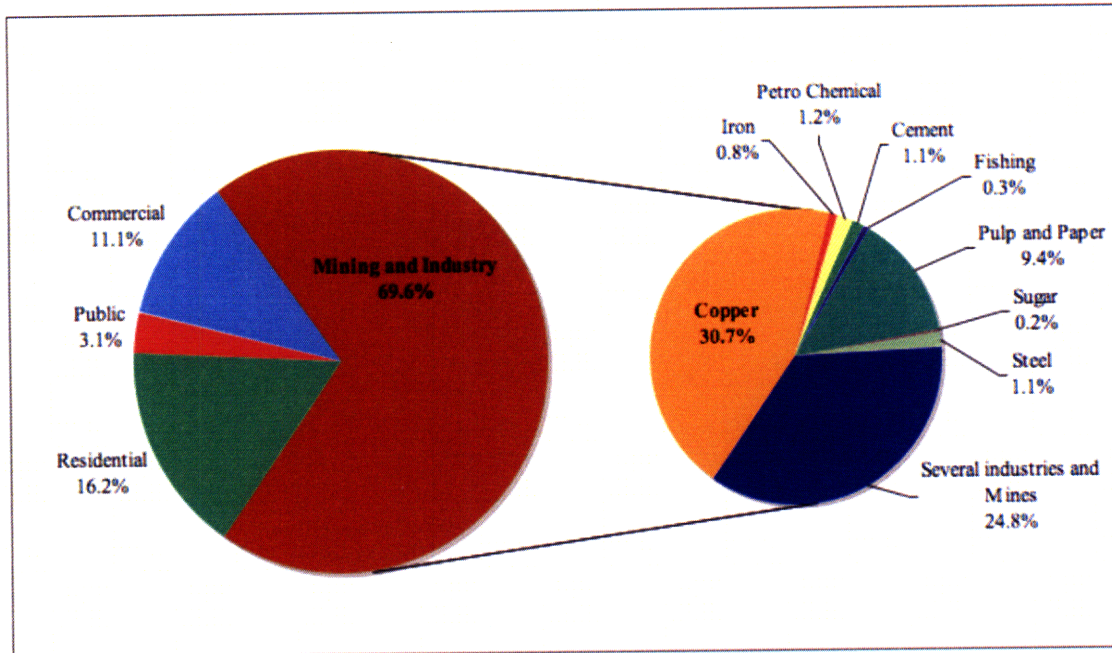
Figure 1-4 Electricity Consumption by Sector, adapted from Universidad de Chile, 2008

1.2.1.1 Electricity Market and Distribution

The Chilean electric industry is entirely privatized and divided into four grids: the Norte Grande Interconnected System (SING), The Central Interconnected System (SIC), the System Aysén, and the System Magellen. The SIC grid accounts for 69% of the electricity and serves 93% of the population, whereas the Aysén grid carries only 0.3% of the country's generation and the SING and Magellen provide 30% and 0.5%, respectively. Endesa-Chile (directly or through subsidiaries) supplies 57% of the SIC and 49% of the country's sold electricity (2001) (GENI, 2002; Universidad de Chile, 2008). Transelec, an electricity company, operates the Chilean transmission system. Transelec owns over 8,000 km of transmission lines and 51 power substations, forming the backbone of Chile's electricity infrastructure. Transelec delivers approximately 99% of the Chilean population through its network of transmission lines (Brookfield Asset Management, 2006). The Aysén generation system is owned and operated solely by Edelaysen S.A., and is comprised of 11.3% thermal, 84% hydroelectric and 4.7% wind (HidroAysén, 2008).

In 1982, Chile's electricity market was divided into generation, transmission and distribution under General Law of Electrical Services (DFL No. 1). The National Energy Commission (CNE) sets the regulatory policies of the electricity sector, ensures compliance, price regulation, and advises government agencies on energy matters. Operation of generating plants and transmission lines is by the Centers of Economic Dispatch Load (CDEC) defined by DFL No. 1 and the Supreme Decree No. 327 (1997); the objective of the CDEC is to preserve security, ensure economical operation, and guarantee right of transmission easements (Universidad de Chile, 2008).

1.2.2. Greenhouse Gas Emissions

Based on an inventory of carbon emissions in Chile (1994), 68% of carbon emissions derive from energy-related activities, 24% are from agriculture and 4% come from both waste and industrial process (Figure 1-5). Forestry is currently a carbon sink in Chile; forest ecosystems absorbed the equivalent of 50% of the countries greenhouse emissions in 1994, or 27.5 million tonnes of carbon dioxide equivalent (tCO_2e, includes CO_2, CH_4, N_2O) (UNFCCC, 2005). The Aysén energy sector emitted 215,000 tCO_2e in 2005, of which 89,000 tCO_2e were from wetlands (primarily as methane), and 15,100 tCO_2e were from waste (landfills, wastewater treatment, human waste) (HidroAysén, 2008).
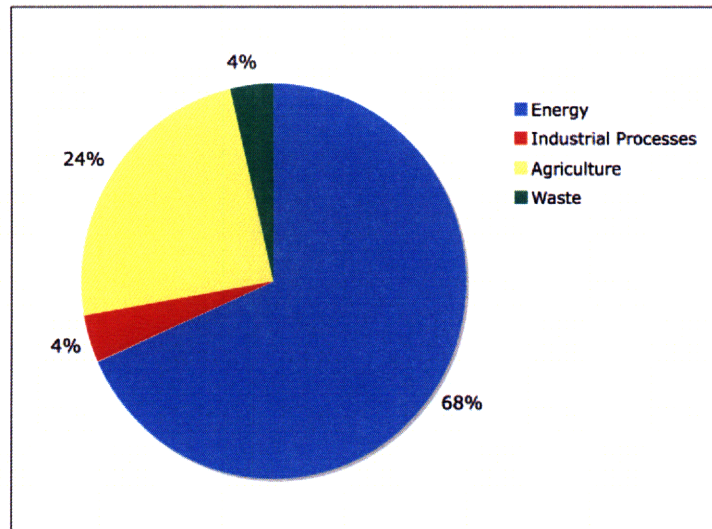
Figure 1-5 Carbon Dioxide Emissions by Sector (1994) (UNFCCC, 2005)

1.3. Project Goal

Understanding the carbon emissions impact of the proposed dams is an important analysis that will allow Chile to consider its energy options quantitatively from an environmental perspective. Although this analysis does not quantitatively consider alternatives such as geothermal, solar or wind power, it defines a method for future analysis. The proposed dams in the Aysén region provide an interesting case study for the larger energy debate, and the outcome could set an important precedent for future energy decisions in Chile.

2. GREENHOUSE GAS ACCOUNTING

The development of a carbon impact analysis is done within the framework of current initiatives, protocols and standards. In particular, guidance is drawn from existing life cycle assessment databases, the Intergovernmental Panel on Climate Change (IPCC), and The World Resource Institute (WRI) and World Business Council for Sustainable Development (WBCSD) accounting protocols.

2.1. Greenhouse Gases

The IPCC considers six anthropogenic greenhouse gases (GHG): carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydroflurocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Carbon dioxide is the most abundant greenhouse gas, however, the global warming impact of each greenhouse gas varies. In accordance with international standard practice, emissions are reported in CO_2-equivalents (CO_2e). Emissions of gases other than CO_2 are translated into CO_2e using global warming potentials; the IPCC recommends using 100-year potentials listed in Table 2-1 (EPA, 2009). This analysis only considers carbon dioxide and methane emissions that result from the proposed dam project.

Table 2-1 Greenhouse Gas Global Warming Potentials (EPA, 2009; Climate Trust, 2005)

Greenhouse Gas[2]		Global Warming Potential
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous Oxide	N_2O	310
Hydroflurocarbons	HFC-134a	1300
Perfluorocarbons	PFCs	5,700-11,900
Sulfur hexafluoride	SF6	22,200

2.2. Accounting Protocols

The World Resource Institute (WRI) and World Business Council for Sustainable Development (WBCSD) have developed protocols for accounting GHG emissions. Currently there are three published protocols: (1) Standard for Corporate Accounting (2) Project Accounting, and (3) Land-use, Land-Use Change, and Forestry (LULUCF) Guidance for GHG Project Accounting (GHGP, 2009).

The standard for corporate accounting is intended for companies who want to report their emissions from corporate operations. Emissions are divided into three categories or scopes; the definition of each is intended to avoid duplication of emissions reporting and to provide a common platform for business accounting. The GHG Protocol for Project Accounting (*Protocol*) was developed for projects that intend to reduce GHG emissions through storage or removal that could be used for the Kyoto Protocol's Clean Development Mechanism (CDM) and the

---

[2] Perfluorocarbons and sulfur hexafluoride global warming potentials from Climate Trust, 2005; all others from EPA, 2009.

application of International Organization for Standardization (ISO) 14060. Projects can have primary or secondary effects. The primary effect is the emissions removal or storage project goal, whereas the secondary effects are unintended GHG sources or sinks that arise from project activity. Secondary effects can occur once (construction, installation, decommissioning) or can occur repeatedly resulting from changes in upstream or downstream systems (GHGP, 2009).

The Protocol for Project Accounting most closely aligns with the objectives of this analysis, therefore, this carbon impact assessment approach loosely follows the five steps outlined in the *Protocol* (GHGP, 2009); the specific approach is detailed in subsequent sections.

1. **Defining the GHG Assessment Boundary:** The assessment boundary encompasses GHG effects that occur as a result of the project. Effects are not limited to a particular geographic region or the controlling interest. Defining the assessment boundary may be an iterative process involving the consideration of important primary and secondary effects.

2. **Identifying the Baseline Candidate:** The process of determining what scenario is the most likely or applicable alternative. For the case of power generation, an alternative power plant could provide the baseline candidate.

3. **Estimating Baseline Emissions:** The baseline scenario is the hypothetical situation that would most likely have occurred without considerations of climate change. Emissions are compared to this baseline to indicate a net reduction or net increase in greenhouse gas emissions. Alternatively, a set of performance standards can be used to measure net benefit.

4. **Monitoring and Quantifying GHG Reductions:** This aspect of a GHG impact assessment can be done through direct measurement or indirect measurements combined with justified calculations. The validity of data and assumptions should be transparent.

5. **Reporting GHG Reductions:** Accurate reporting on each step of the project accounting process is important to receive credit for GHG mitigation.

Because neither the project (HidroAysén dams), nor the baseline (natural gas plants) is fully designed, carbon emissions are estimated for both cases given the available information. The *Protocol* is also typically designed for individuals working directly with the project proponents, and assumes that onsite data collection and studies are possible to compliment the emissions inventory. In this case, information about the proposed dams is limited to the data published by HidroAysén, the project proponent, in the Environmental Impact Assessment (EIA). Additionally, reporting presented in this study is done for transparency, and not with the intention of receiving carbon credits.

2.3. The Project: HidroAysén Hydroelectric Dams

HidroAysén S.A. is a joint venture between Endesa Chile, a Spanish energy company, and Colbun S.A., a Chilean electricity generation company (HidroAysén, 2007). The HidroAysén project consists of five hydroelectric dams on two rivers: the Rio Baker and the Rio Pascua. The combined capacity of the dam system is 2,750 MW, and will generate (on average) 18,430 GWh

of power annually, the equivalent of 30% of the power currently installed in the SIC. Power generated by the dams will be connected through local transmission mains; a high voltage transmission line will connect the dams in the Aysén grid to the northern SIC grid (HidroAysén, 2008). The dams will require inundation of land for the five reservoirs totaling a flooded area of 5,910 ha. In addition to flooded land, the construction and operation of the dam will disturb 11,000 ha of land. A summary of each dam and the total project impact is shown in Table 2-2.

Project information is primarily found in the Environmental Impact Assessment (EIA), an 11,000-page report completed by HidroAysén in 2008 in accordance with Chilean law. It is assumed that the dam will operate for 25 years to match the baseline natural gas scenario. However, because dams can operate for more than 50 years (HidoAysen, 2008), the implication of a 50-year dam is discussed in Section 7 Results.

Table 2-2 Hydroelectric Project Summary (HidroAysén, 2008)

	Units	Baker 1	Baker 2	Pascua 1	Pascua 2.1	Pascua 2.2	Total
Region	-	Chacabuco	El Saltón	Lago Chico	Rio Pascua	San Vicente	-
Capacity	MW	660	360	460	770	500	2,750
Maximum Operation	meters	200	93	266	200	101	-
Dam Area - Reservoir	hectares	710	3,600	500	990	110	5,910
Extent of Impact Incl. Reservoir	hectares	2,412	9,137	1,247	3,210	977	16,983
Design Flow	m3/s	927	1,275	880	980	980	-
Design Flow	L/s	927,000	1,275,000	880,000	980,000	980,000	-
Power Plant Capacity	MW	660	360	460	770	500	2,750
Average Annual Energy	GWh	4,420	2,530	3,020	5,110	3,350	18,430

2.3.1. Transmission Lines

A local electricity grid will combine the output from the five dams and will be converted from alternating current (AC) to direct current (DC) for long distance transmission (HidroAysén, 2008). The 2,240 km transmission line will require over five thousand 50-meter towers spaced 400 meters apart and requiring a 70-meter easement (Patagonia without Dams Campaign). As a result of the separation of generation, transmission and distribution under the General Law of Electrical Services, Transelec will design the high voltage transmission line separately from the HidroAysén dams. CONAMA (Chilean equivalent to the U.S. Environmental Protection Agency) will therefore evaluate the environmental impact of the dams and the transmission line

separately. Because the success of the dam project is contingent on the high voltage transmission line, the impact is included in this carbon analysis.

The transmission lines themselves have been the greatest source of controversy. Although detailed designs are likely developed, they have not yet been made publicly available. One key question is the total capacity of the DC line; if the capacity is greater than the 2,750 MW dam project, this may encourage subsequent development in the rural region between Aysén and Santiago (S.J. Wright, personal communication, 2009).

2.4. Assessment Boundary

The carbon dioxide impact analysis assessment boundary includes emissions from land-use change, materials, construction, and operation as summarized herein:

1. **Construction** – emissions related to the construction of each power facility including equipment and machinery, and transport of personnel by bus and plane.

2. **Materials** – embedded energy of materials used to construct each power facility.

3. **Land-use** – emissions caused by inundation of the dam reservoirs, and loss of carbon sink and release of stored carbon as a result of deforestation.

4. **Operation** – Emissions from power plant operation and fuel transport.

2.5. The Baseline Candidate: Natural Gas

Based on the energy situation in Chile, it is assumed that several natural gas plants would be a direct replacement for the proposed dams. It is assumed that natural gas plants will be located between Santiago and the LNG terminal near the small coastal community of Horcon. For the purpose of these calculations, the location of the natural gas facility is assumed to be 100 km from Santiago; the availability or suitability of land for the construction of these plants is not a part of this analysis. It is assumed that construction of transmission lines will be minimal and that natural gas plants can connect directly to the existing power grid. This assumption is intended to simplify this analysis and is not based on an analysis of the capacity or extent of the SIC grid.

If the dams are not constructed, it is assumed that natural gas plants will need to replace the average electricity that is delivered through the transmission system from the dam project. The combined capacity of the proposed dam system is 2,750 MW, and will generate (on average) 18,430 GWh of electricity each year. The nameplate capacity of the equivalent natural gas plant is based on the delivered electricity, the theoretical output of a natural gas facility and the capacity factor of 0.60 for a typical combined cycle natural gas plant (UMass Amherst). The percent transmission loss for DC transmission is 3% per 1000 km of line (Wikipedia, 2009b); or 6.7% for the 2,240 km proposed system. The equivalent natural gas plant is 3,270 MW as shown in the following calculations:

Nameplate Capacity Natural Gas (MW) = Theoretical Output (MW)/Capacity Factor

$$NameplateCapacity_{NaturalGas} = \frac{1,960\,MW}{0.60} = 3,270\,MW$$

where:

Theoretical Output Natural Gas (MW) = Delivered Electricity Dam (GWh/yr) × 1/365.25 yr/day × 1/24 day/hour × 1000 MW/GW

$$TheoreticalOutput_{NaturalGas} = 17,200\frac{GWh}{yr} \times \frac{1}{365.25}\frac{yr}{day} \times \frac{1}{24}\frac{day}{hour} \times 1000\frac{MW}{GW} = 1,960\,MW$$

where:

Delivered Electricity Dam = Annual Electricity Output (GWh/yr) × (1-transmission losses)

$$DeliveredElectrictity_{Dam} = 18,430\frac{GWh}{yr} \times (1-0.067) = 17,200\frac{GWh}{yr}$$

A typical natural gas power plant is on the order of hundreds of megawatts not thousands, therefore multiple natural gas plants will be required. However, calculations are based on per MW averages for natural gas plants and the distinction between the different power plants are not explicit. Natural gas will be shipped in tankers as liquefied natural gas and re-gasified for use at the power plants. The emissions from both the tanker transport and operation of the plants will be considered in addition to construction, land-use change and material emissions.

2.6. Baseline and Project Emissions

Both scenarios (hydroelectric and natural gas) are defined based on the four emissions categories: land-use, materials, construction, and operation. Information regarding the HidroAysén project is based on the 2008 Environmental Impact Assessment (EIA) and information gained through discussions with local authorities and contacts. Due to insufficient data on the transmission line, assumptions are based on typical transmission line design. Assumptions regarding the natural gas plant are based on local information when possible, and U.S. Energy data when Chilean information is not available.

Emissions are calculated using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (*Guidelines*). Specifically, Volume 2: Energy and Volume 4: Agriculture Forestry and Other Land-use are used. The *Guidelines* present three tiers of methods with varying levels of complexity. The Tier chosen is based on the available data and the importance of the category. Tier 1 is the basic method, Tier 2 is the intermediate, and Tier 3 the most complex; higher tiers are considered to be more accurate. In general, the Tier 1 approach is used in this analysis due to data limitations.

2.7. Emission Factors and Units

The combustion of fuel results in carbon dioxide emissions based on the fuel type and the quantity burned. The emission factors summarize by fuel in Table 2-3 are used extensively in the carbon emissions calculations.

Table 2-3 Emission Factors by Fuel (adapted from IPPC, 2006)

Fuel	Emission Factor (kg CO_2/TJ)
Diesel	74,100
Motor Gasoline	69,300
Jet Kerosene	71,500
Aviation Gasoline	69,300

All calculations are done in units of kilograms of greenhouse gas consistent with IPCC emission factors, and then converted to and reported in metric tonnes of carbon dioxide equivalents (tCO_2e), where 1 tonne (t) = 1000 kilograms (kg).

3. CONSTRUCTION EMISSIONS

The construction emissions are divided into two categories:

1. **Construction Equipment and Machinery**– these emissions can be from stationary equipment running on diesel engines or from stationary equipment that is hooked up to electric generators.

2. **Transport of the Workforce** – large infrastructure projects require a significant workforce. The mobile emissions from transporting workers between home and worksite are included.

The construction equipment and machinery is based on the total fuel needed during construction, whereas the transport of the workforce is based on the schedule of workers and transport method. For the dams, workers will be bused and flown whereas for the natural gas plant only buses will be used to transport workers.

3.1. HidroAysén Project

The construction of the HidroAysén dams will occur over 12.5 years (HidroAysén, 2008), and will result in carbon dioxide emissions from construction equipment and machinery, and transport of personnel. A sixth hydroelectric facility, Del Salto, will be constructed to provide electricity for the construction of the Baker 1 dam (HidroAysén, 2008). The construction equipment and materials needed to build the Del Salto dam are included in construction totals, but an in depth analysis of this project is not included.

3.1.1. Construction Equipment and Machinery

A variety of construction equipment and machinery is needed, including, but not limited to, front loaders, bulldozers, backhoes, cranes, drills, pumps, mixer trucks, hopper trucks, flat trucks, and concrete plants. The volume of emissions from construction equipment and machinery is estimated using the amount of fuel inputs required for the construction project. Another approach would be to conduct detailed emissions analysis by equipment type and hours of operation; this level of detail is not considered feasible without detailed specifications of the equipment. Calculations are consistent with the IPCC *Guidelines* (Tier 1) for off-road mobile combustion emissions. Emissions from the construction equipment and machinery during the construction of the dam are 872,000 tCO$_2$, as shown:

Emissions (tCO$_2$) = Fuel Consumed (TJ) × Fuel Emission Factor (kg CO$_2$/TJ) × 10^{-3} tonne/kg

$$Emissions = 11,770 TJ \times 74,100 \frac{kgCO_2}{TJ_{diesel}} \times 10^{-3} \frac{tonne}{kg} = 872,000 tCO_2$$

Fuel Consumed (TJ) = Fuel Inputs (L) × Energy Density (MJ/L) × 10^{-6} TJ/MJ

$$FuelConsumed = 328{,}780{,}000 L \times 35.8 \frac{MJ}{L_{diesel}} \times 10^{-6} \frac{TJ}{MJ} = 11{,}770 TJ$$

Where:

Fuel Inputs = 328,780,000 liters of fuel is required for the construction of the dams (HidroAysén, 2008), of which, 100% is assumed to be diesel; and

Energy Density = 35.8 MJ/L for diesel fuel (MIT Energy Club, 2007).

3.1.2. Transport of Workforce

Due to the high manpower requirements, most staff will come from the central region of Chile and stay in camps during construction. HidroAysén will have an average workforce of 2,400 people during the 12.5 years of construction with a peak between year four and five of 5,100 workers (visual estimation based on worker requirements presented in the EIA as seen in Figure B-1; HidroAysén, 2008).

The workers will be divided into three teams, each team consisting of roughly 800 people. Each team will work 20 days on and 10 days off in Santiago (J. Leidich, personal communication, 2009). The schematic illustrates the transport of personnel every ten days where the dotted line represents 800 workers; solid line represents 400 workers. Black lines are the people returning to work and blue lines are those going on break.

Therefore, every ten days, of the 800 workers coming back from break:

- 800 people will fly from Santiago to Balmaceda (1600 km). Of those 800 people:

    - 400 people will be transported by bus from Balmaceda to Cochrane (360 km), and

    - 400 people will be transported by bus from Balmaceda to Pascua (520 km).

Every ten days, of the 800 workers going on break:

- 800 people will fly from Balmaceda to Santiago (1600 km). Of those 800 people:

    - 400 people will have been transported by bus from Cochrane to Balmaceda (360 km), and

    - 400 people will have been transported by bus from Pascua to Balmaceda (520 km).
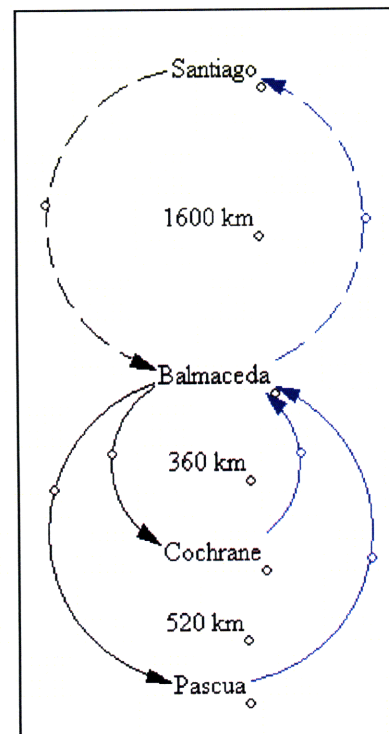
Trips distances are one-way; the buses that will drop people off at the Balmaceda airport will return with passengers who just arrived at the airport.

Carbon dioxide emissions related to the transport of workers are considered for two types of transport: buses to transport workers from camps to the field, and airplanes to fly workers between the Aysén region and their homes in Santiago. These calculations do not include the emissions that result from daily transport between the work camp and worksite for the dam project.

3.1.2.1 Calculations: Bus Transport

Every ten days 800 people will travel 360 km by bus between Cochrane and Balmaceda (400 traveling each way) and an additional 800 people will travel 520 km by bus between Pascua and Balmaceda (400 traveling each way) for a roundtrip total of 1,760 km/bus (520 km × 2 + 360 km × 2). For a typical passenger bus (55 person capacity), 7.3 buses will be required each trip. Although fractional buses does not make logical sense, it is assumed that the buses will be filled when possible and that given the fluctuating workforce, this value will represent the average number of buses/trip.

For 7.3 buses traveling 1,760 km each trip and making 36.5 trips/year, the total distance traveled by bus each year is 469,000 km:

$$Distance_{Bus} = \frac{365.25}{10}\frac{trip}{yr} \times 1,760\frac{km}{bus} \times 7.3\frac{bus}{trip} = 469,000\frac{km}{yr}$$

The emissions associated with these bus trips are calculated based on the total fuel consumed and an emission factor for diesel fuel. The diesel fuel consumed for bus transport of personnel over the 12.5-year construction is 86TJ, which corresponds to 6,370 tCO_2:

Bus Emissions (tCO_2) = Fuel Consumed (TJ) × Emission Factor (kg CO2/TJ) × 10^3 (kg/tonne)

$$Emissions = 86TJ \times 74,100\frac{kgCO_2}{TJ_{diesel}} \times \frac{1}{1000}\frac{kg}{tonne} = 6,370tCO_2$$

Fuel Consumed (TJ) = Distance (km/yr) ×Fuel Efficiency (MJ/km) × 10^{-6}(TJ/MJ) ×Construction Duration (yr)

$$FuelConsumed = 469,000\frac{km}{yr} \times 14.7\frac{MJ}{km} \times 12.5yr \times 10^{-6}\frac{TJ}{MJ} = 86TJ$$

Where, based on a study conducted by a commuter service in Santa Barbara, it is assumed that hethe average 55-seat diesel bus has a fuel efficiency of 14.7 MJ/km[3] (NREL, 2000).

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[3] The study reported 6.0 miles per diesel equivalent gallon or per 135,000 BTU. Converting to metric units gives 9.66 km per142 MJ = 0.068 km/MJ or 14.7 MJ/km.

3.1.2.2 Calculations: Aviation Transport

The transport of personnel to and from Santiago (roundtrip distance of 3,200 km) will result in a total annual flying distance of 619,500 km. This is based on the need for 5.3 planes/trip to transport 800 people on Airbus 320 (A320) airplanes with a capacity of 150 passengers (Airliners.net, 2009).

$$Distance_{Plane} = \frac{365.25}{10} \frac{trip}{yr} \times 3200 \frac{km}{plane} \times 5.3 \frac{plane}{trip} = 619,500 \frac{km}{yr}$$

Calculations are based on the IPCC *Guidelines* Tier 2 approach for domestic aviation transport. The Tier 2 method divides emissions into two categories: landing/take-off (LTO) and cruise emissions. The one-way plane trip on an A320 between Balmaceda and Santiago requires 7,780 kg fuel given the fuel efficiency of 4.86 kg/km (Airliners.net, 2009). The LTO requires 2,440 kg of fuel (IPCC, 2006), which is 24% of the total flight fuel consumption. The A320 consumes jet kerosene, a fuel used in all jet airplanes, therefore the default emission factor of 71,500 kg $CO2/TJ$ is used (IPCC, 2006). The aviation transport of personnel over the 12.5-year construction period contributes 36,800 tCO_2.

Total Aviation Emissions

Total Emissions (kg CO₂) = (LTO Emissions + Cruise Emissions) (kgCO2/yr) × Construction Duration (yr) ×10⁻³ (tonne/kg)

$$TotalEmissions = \left(2,931,500 \frac{kg_{CO2}}{yr} + 11,440 \frac{kg_{CO2}}{yr}\right) \times 12.5yr \times 10^{-3} \frac{tonne}{kg} = 36,800 t_{CO2}$$

LTO Emissions

LTO Emissions (kg CO₂/yr) = LTO Fuel Consumption (kg fuel/yr) ×Emission Factor LTO (kg CO₂/kg fuel)

$$LTOEmissions = 41 \frac{TJ}{yr} \times 71,500 \frac{kg_{CO2}}{TJ} = 2,931,500 \frac{kg_{CO2}}{yr}$$

LTO Fuel Consumption (TJ/yr) = Number of LTOs (LTO/yr) × Fuel Consumption per LTO (kg fuel/LTO) × Fuel Energy Density (MJ/kg fuel) × 10⁻⁶ (TJ/MJ)

$$LTOFuelConsumption = 387 \frac{LTO}{yr} \times 2,440 \frac{kg_{fuel}}{LTO} \times 43.2 \frac{MJ}{kg_{fuel}} \times 10^{-6} \frac{TJ}{MJ} = 41 \frac{TJ}{yr}$$

Where the number of LTO/yr is:

$$LTOs = 5.3 \frac{planes}{trip} \times 36.5 \frac{trips}{yr} \times 2 \frac{LTO}{plane} = 387 \frac{LTO}{yr}$$

Cruise Emissions

Cruise Emissions (kg CO₂/yr) = Cruise Fuel Consumption (kg fuel/yr) × Emission Factor Cruise (kg CO₂/kg fuel)

$$CruiseEmissions = 0.16\frac{TJ}{yr} \times 71{,}500\frac{kg_{CO2}}{TJ} = 11{,}440\frac{kg_{CO2}}{yr}$$

Cruise Fuel Consumption (TJ/yr) = Travel Distance (km/yr) × Fuel Efficiency (MJ/km) × 10⁻⁶ (TJ/MJ)

$$CruiseFuelConsumption = 619{,}500\frac{km}{yr} \times 0.26\frac{MJ}{km} \times 10^{-6}\frac{TJ}{MJ} = 0.16\frac{TJ}{yr}$$

Where the fuel efficiency is 0.26 MJ/km; derived from 0.39 mpg (Airliners.net, 2009) and density (804 kg/m3) and energy density (43.2 MJ/m3) of Jet Kerosene (Wikipedia, 2009a).

3.2. Construction: Natural Gas Baseline

A typical natural gas plant is around 400 MW and is constructed in roughly three years.[4] The emissions from construction equipment and machinery and the bus transportation of workforce are detailed herein.

3.2.1. Construction Equipment and Machinery

Similar to the 12.5-year construction of hydroelectric dams, equipment and machinery will be required over the 3-year construction period of a natural gas plant. It is assumed that a similar scale of equipment and machinery will be required, but for a shorter duration. Assuming a linear relationship between fuel consumption and construction years, a fraction (3/12.5) of the fuel will be consumed during the construction of a natural gas plant. Based on this assumption, the construction project will require 78.9 million liters of fuel, and it is assumed 100% of the fuel is diesel, which has an energy density 35.8 MJ/L (MIT Energy Club, 2007).

The diesel fuel consumed for bus transport of personnel over the 3-year construction is 2,825TJ, which corresponds to 209,000 tCO₂:

Emissions (tCO₂) = Fuel Consumed (TJ) × Fuel Emission Factor (kg CO₂/TJ) × 10⁻³ tonne/kg

$$Emissions = 2{,}285TJ \times 74{,}100\frac{kgCO_2}{TJ_{diesel}} \times 10^{-3}\frac{tonne}{kg} = 209{,}000tCO_2$$

_____

[4] Based on conversations with industry engineer Tom Parker (Personal Communication, 2009).

$$\textit{Fuel Consumed (TJ)} = \textit{Fuel Inputs (L)} \times \textit{Energy Density (MJ/L)} \times 10^{-6} \, TJ/MJ$$

$$FuelConsumed = 78{,}910{,}000L \times 35.8 \frac{MJ}{L_{diesel}} \times 10^{-6} \frac{TJ}{MJ} = 2{,}825TJ$$

3.2.2. Transport of Workforce

It is assumed that workers will be bused daily from their homes in Santiago, approximately 100 km northwest to a natural gas plant site; the roundtrip daily distance driven is 200 km. It is assumed that roughly 2,850 workers[5] (on rotation) work 7 days per week 52 weeks of the year for three years. For a typical passenger bus (55 person capacity), 51.8 buses will be required each trip to transport 2,850 workers each trip

The total distance traveled by bus each year is 3,780,000 km:

$$Distance = 365.25 \frac{trip}{yr} \times 200 \frac{km}{bus} \times 51.8 \frac{bus}{trip} = 3{,}780{,}000 \frac{km}{yr}$$

The emissions associated with these bus trips are calculated based on the total fuel consumed and an emission factor for diesel fuel. The diesel fuel consumed for bus transport of personnel over the 3-year construction is 167TJ, which corresponds to 12,400 tCO_2 emitted.

$$\textit{Bus Emissions (tCO}_2\textit{)} = \textit{Fuel Consumed (TJ)} \times \textit{Emission Factor (kg CO2/TJ)} \times 10^{-3} \textit{ (kg/tonne)}$$

$$Emissions = 167TJ \times 74{,}100 \frac{kgCO_2}{TJ} \times \frac{1}{1000} \frac{kg}{tonne} = 12{,}400 tCO_2$$

$$\textit{Fuel Consumed (TJ)} = \textit{Distance (km/yr)} \times \textit{Fuel Efficiency (MJ/km)} \times 10^{-6}\textit{(TJ/MJ)} \times$$
$$\textit{Construction Duration (yr)}$$

$$FuelConsumed = 3{,}780{,}000 \frac{km}{yr} \times 14.7 \frac{MJ}{km} \times 10^{-6} \frac{TJ}{MJ} \times 3yr = 167TJ$$

Where, based on a study conducted by a commuter service in Santa Barbara, it is assumed that the average 55-seat diesel bus has a fuel efficiency of 14.7 MJ/km[6] (NREL, 2000).

3.3. Summary and Sensitivity

Construction of the hydroelectric dams and the baseline natural gas facility (Table 3-1) show that fuel for equipment and machinery is the dominant source of carbon emissions contributing 95% of the dam construction emissions and 94% of the natural gas construction emissions. The

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[5] Assumes large infrastructure projects require a similar labor force (per MW). Therefore 0.87 ppl/MW (2400ppl/2750 MW) is applied for the 3,270MW natural gas plant resulting in 2,845 workers.
[6] The study reported 6.0 miles per diesel equivalent gallon or per 135,000 BTU. Converting to metric units gives 9.66 km per142 MJ = 0.068 km/MJ or 14.7 MJ/km.

hydroelectric construction emissions are four times greater than the natural gas construction emissions; given the assumptions, this can be attributed to the much longer construction duration (12.5 years versus 3 years).

The emissions associated with the bus and plane transport of personnel are relatively small. Despite the intensive air travel required to transport workers for the dam project, this only contributes to 4% of the total construction emissions. The dam transport emissions are 3.5 times greater than those for natural gas.

Table 3-1 GHG Contribution from Construction Operations

Emissions Source	GHG Contribution (tCO$_2$e)	
	HidroAysén	Natural Gas
Construction Equipment and Machinery	872,000	209,000
Bus Transport of Personnel	6,370	12,400
Aviation Transport of Personnel	36,800	-
Total	*915,000*	*221,000*

For the hydroelectric dams, fuel consumption data is provided but the fuel type is not specified. The assumption that all fuel is diesel could affect the total emissions; as shown in Table 2-3, diesel has the highest emission factor of the fuels considered, with gasoline and jet kerosene 6.5% and 3.5% lower, respectively. Although most heavy equipment does run on diesel, it is expected that aviation gasoline or jet kerosene will be used for helicopter transport, and that some equipment may run on motor gasoline therefore reducing the total emissions. This error is magnified in the case of the dam project due to the longer construction duration.

A larger source of error is the assumption about the amount of fuel used for the construction of natural gas plants, this value is somewhat arbitrary, and in reality, equipment for the dams in a rural area may be more intensive than requirements to build a natural gas plant outside of a metropolitan area. A more refined estimate could be developed with access to construction documents for a Chilean natural gas plant.

The emissions from the transport of equipment from Santiago or elsewhere to the Aysén region are not included in these calculations. However, it is suspected that these emissions are greater for the dam project than the natural gas alternative, given its rural location.

4. EMBEDDED ENERGY OF MATERIALS

The embedded energy (or embodied energy) of materials is the amount of energy required over the lifecycle of a product or material. For instance, the embedded energy of concrete includes energy associated with inputs (cement and aggregate), production (concrete plant), distribution (distance traveled by vehicle type) and disposal (landfill or recycling plant). A life cycle assessment (LCA) is one approach to determining the embodied energy of products; an LCA looks at the inputs/outputs of a product given a particular boundary and location. The material embedded energy for the hydroelectric dams, the transmission line and the natural gas plants are calculated given the construction material inputs, and the energy cost of each material (the embedded energy) estimated by Smil (2008).

4.1. HidroAysén Project

Material inputs include concrete, iron rebar, explosives, tires, and batteries, among other things (HidroAysén, 2008). The embedded energy for concrete, iron and explosives used in the project are calculated as the total quantity of material used, multiplied by the energy cost of that material as estimated by Smil (2008), and converted into a carbon cost using Chile's emission factor. A summary of the carbon cost of materials for dams is shown in Table 4-1. The majority of embedded energy is a result of the extensive concrete needed for the dams; in total 446,000 tCO_2 are emitted due to the embedded energy of the materials required.

An example calculation for the carbon cost of iron in the dams is provided:

Carbon Cost (tCO2) = Quantity of Iron (tonnes) × Energy Cost of Iron (MJ/tonne) × Emission Factor (tCO2/MJ)

$$CarbonCost = 7,650tonne \times 22,500\frac{MJ}{tonne} \times 0.0000498\frac{tCO_2}{MJ} = 8,570tCO_2$$

Where Chile's emission factor is based on the carbon dioxide emissions from the consumption and flaring of fossil fuels divided by the primary energy consumption in 2006 (EIA, 2006):

$$EmissionFactor = \frac{64,800,000}{1,320,000,000,000}\frac{tCO_2}{MJ} = 0.0000498\frac{tCO_2}{MJ}$$

Table 4-1 Dam Material Inputs (HidroAysén, 2008)

Input	Quantity[7] (tonnes)	Energy Cost (MJ/tonne)[8]	Energy Cost (MJ)	Carbon Cost (tCO2)
Concrete (Cement and Aggregate)	4,337,791	2,000	8,675,582,000	432,000
Explosives	2,890	40,000	115,600,000	5,760
Iron	7,650	22,500	172,125,000	8,570
Total				*446,000*

4.2. Transmission Line

Aluminum alloys are often used for electrical transmission lines, even though the conductivity is only 60% that of copper. Aluminum alloys are 99% aluminum but have small amounts of copper, magnesium, silicon, manganese and other elements to improve the conductivity and other properties (Los Alamos National Laboratory, 2003).

A life cycle assessment (LCA) by Blackett et al. (2008) compared the material embedded energy of electric transmission systems in England and Wales. Towers and conductor cable were analyzed for high voltage transmission systems.

Conductor Cable: Conductors are made of Rubus aluminum alloy, 6101 grade aluminum with 0.5% magnesium and 0.5% silicon. The Rubus consists of sixty-one 3.5 m diameter strands; for every 10 km of cable, 15,690 kg of aluminum and 79 kg of magnesium and silicon are used. The study concluded that the conductor cable had a greenhouse effect of 550 tCO_2e/10-km of cable (Blackett et al., 2008).

For 2,240 km of transmission lines, 224 ten-kilometer cable segments are needed for one cable. Assuming six parallel cables, 1,344 ten-kilometer cable segments (224 ten-km cable segments/cable × 6 cables) are needed and the embedded energy of the transmission line cable is 739,000 tCO_2e.

$$CableEmbeddedEnergy = 1,344\,segments \times 550\frac{tCO_2e}{segment} = 739,000tCO_2e$$

Lattice Towers: The steel towers are 50-meters high and constructed from galvanized mild steel, without paint, and are expected to last 45 years in rural or non-polluted environments. The lattice tower is comprised of two main materials: mild steel and zinc. Based on the material composition of the towers, the life cycle greenhouse gas cost of one lattice tower is 17 tCO_2e (Blackett et al., 2008).

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[7] Adapted from Table 1.3-3 of HidroAysén, 2008.
[8] Average values adapted from Table A.12 of Vaclav Smil, 2008.

The 2,240 km DC transmission line will require 5,625 fifty-meter towers spaced 400 meters apart (Patagonia without Dams Campaign). The embedded energy of these towers is 95,000 tCO$_2$e:

$$TowerEmbeddedEnergy = 5,625 towers \times 17 \frac{tCO_2e}{tower} = 95,600 tCO_2e$$
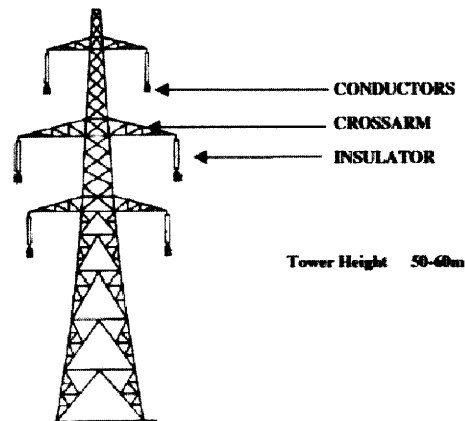
Figure 4-1 High Voltage Transmission Tower (Blackett et al., 2008)

The total embedded energy in the cable and lattice towers for the high voltage transmission line is 839,000 tCO$_2$e.

4.3. Natural Gas Baseline

Material inputs for the baseline natural gas power plant are adapted from the Ecoinvent System Processes database, accessed through SimaPro provided by PRé Consultants. The data set used is titled: Gas power plant, 300MW2/GLO/I U. This database lists quantities of important materials (aluminum, concrete, copper and steel) used in construction of an average 300 MW gas power plant (PRé Consultants, 2009); material quantities are scaled for the 3,270 MW baseline power plant. The embedded energy of materials is calculated using the energy cost of materials; the carbon cost of materials is found using a country emissions factor of 0.0000498 tCO$_2$/MJ (Table 4-2).

29

Table 4-2 Embedded Energy of Natural Gas Power Plant

Input	Quantity[9] (tonnes)	Energy Cost[10] (MJ/tonne)	Energy Cost (MJ)	Carbon Cost (tCO2)
Aluminum	2,450	210,000	514,500,000	25,600
Concrete (Cement and Aggregate)	62,800	2,000	125,600,000	6,260
Copper	2,450	105,000	257,250,000	12,800
Steel	18,000	22,500	405,000,000	20,200
Total				*39,300*

Example calculation:

Carbon Cost (tCO2) = Quantity of Aluminum (tonnes) × Energy Cost of Iron (MJ/tonne) ×
   Emission Factor (tCO2/MJ)

$$CarbonCost = 2,453 tonne \times 210,000 \frac{MJ}{tonne} \times 0.0000498 \frac{tCO_2}{MJ} = 257,000 tCO_2$$

In total 39,300 tCO2 are emitted due to the embedded energy of the materials required for the construction of a 3,270 MW natural gas powered plant.

4.4. Summary and Sensitivity

The embedded energy of materials is summarized in Figure 4-2. The transmission line has 1.9 times the embedded energy of materials in the dams and 21 times the embedded energy of the natural gas plants. Of the 446,000 tCO$_2$e associated with the embedded energy of the dams, 97% is due to concrete with only 3% from explosives and iron. Of the 839,000 tCO$_2$e associated with the transmission line materials, 89% are attributed to the aluminum alloy cable, and only 11% to the steel towers. The natural gas plant embedded energy (39,300 tCO$_2$e) is attributed to aluminum (65%), reinforcing steel (50%), copper (33%) and concrete (16%). The concrete needs for the dams is 69 times greater than the concrete needed to build the natural gas plant.

Although the dams require an extensive amount of concrete, the embedded energy of concrete is small (2,000 MJ/tonne). Conversely, the transmission lines require less material but a significant amount of aluminum, which has a high energy cost (210,000 MJ/tonne).

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[9] Adapted from Ecoinvent System Processes database for Gas power plant, 300MW2/GLO/I U.
[10] Average values adapted from Table A.12 of Vaclav Smil, 2008.

Although not all materials will be made in Chile, the majority (concrete) will likely be made onsite, justifying the use of a Chile-specific emission factor, however other materials may come from more carbon intense economies. For instance, the U.S. emission factor is 13% greater than Chile's (EIA, 2006). To further refine the carbon intensity and embedded energy values for this analysis, a full life cycle assessment would be required.
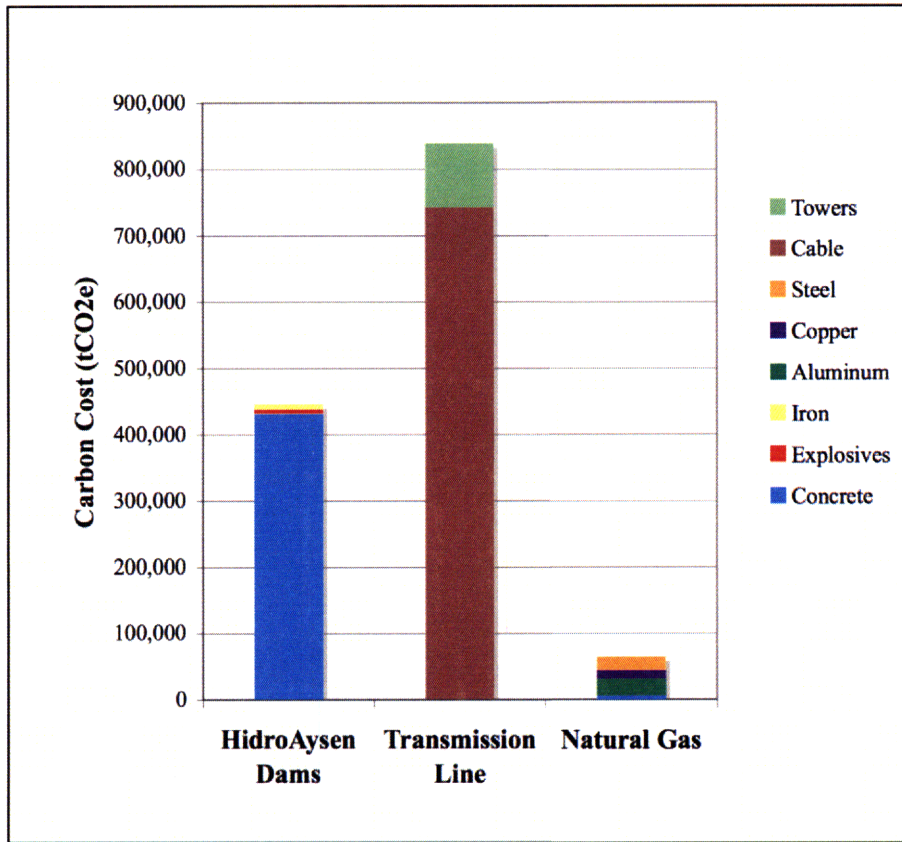
Figure 4-2 Embedded Energy Carbon Cost

Similarly, the LCA of transmission lines was done for the National Grid system in England and Wales and therefore is not specific to Chile. However, it is assumed that the approach provides valid order of magnitude estimates.

The materials embedded energy cost estimates assume that steel and aluminum are not recycled. If recycled steel and aluminum were used in the construction of the transmission line and the natural gas plant, the embedded energy of materials would be lower. The energy cost of recycled aluminum is 8.4 times less than aluminum from raw resources. Further, the transmission lines may use copper cables, particularly considering Chile's copper industry; the energy cost of copper is half that of aluminum. Understanding the material inputs and the extent of recycled material used would be a useful refinement to this analysis.

5. LAND-USE CHANGE

Land-use change calculations focus on the deforestation that results from development of the dam system proposed by HidroAysén, the transmission system, and the natural gas alternative. For five dam system, the carbon impact of flooding the land to create reservoirs is also estimated.

5.1. Deforestation

Emissions from land-use change are estimated based on projected changes in the carbon cycle of terrestrial ecosystems related to deforestation. Carbon flows between the five carbon pools within the system (above ground biomass, below ground biomass, litter, dead wood and soil organic matter) and into and out of the system (Figure 5-1) (IPCC, 2006).

Plants naturally photosynthesize and during this process CO_2 is removed from the atmosphere and absorbed by the plants to make carbohydrates. Most of the carbon is cycled back into the atmosphere during decomposition. The IPCC estimates that the world's ecosystems absorb approximately one billion tonnes of carbon annually (net); this is roughly equal to one-sixth of anthropogenic carbon emissions (Litynski et al., 2006). However, the rate of carbon sequestration varies significantly by tree species and geographic location. Carbon accumulation occurs more rapidly in young trees that are actively growing and gaining carbon stock as wood. When a tree reaches maturity, the rate of carbon uptake and the rate of respiration become similar, and old trees may in fact release more CO_2 than they capture (Rousseau, 2008).

Studies by Fargione et al. (2008) considered the 'carbon debt[11]' from converting existing land to agriculture for biofuels production activities. The studies showed that the carbon released from land conversion could be as large as 3,452 tCO_2/ha, but values ranged significantly. In the case of converting land for biofuels production, the act of land change is a much greater net GHG emitter than the fossil fuels they are typically displacing. Therefore, considering land-use changes in any alternative energy option is crucial to understanding the true carbon benefit.

Additionally, the IPCC considers preventing deforestation an important issue in the context of climate change mitigation, particularly in developing countries (UNFCCC). Forestry plays a particularly important role in Chile's carbon balance: in 1994, land-use change and forestry offset 50% of the country's annual emissions (UNFCCC, 2005).

Because carbon stocks are greatest on forested land (IPCC, 2006), deforestation is the primary focus of emissions associated with land-use change. To determine the land-use impact of the dams, transmission line and natural gas baseline, carbon emissions from (1) the release of stored carbon from clear-cutting forests and (2) the loss of carbon sequestration after deforestation, are considered.

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[11] Carbon dioxide released during the first 50-years of the biofuels process activities.
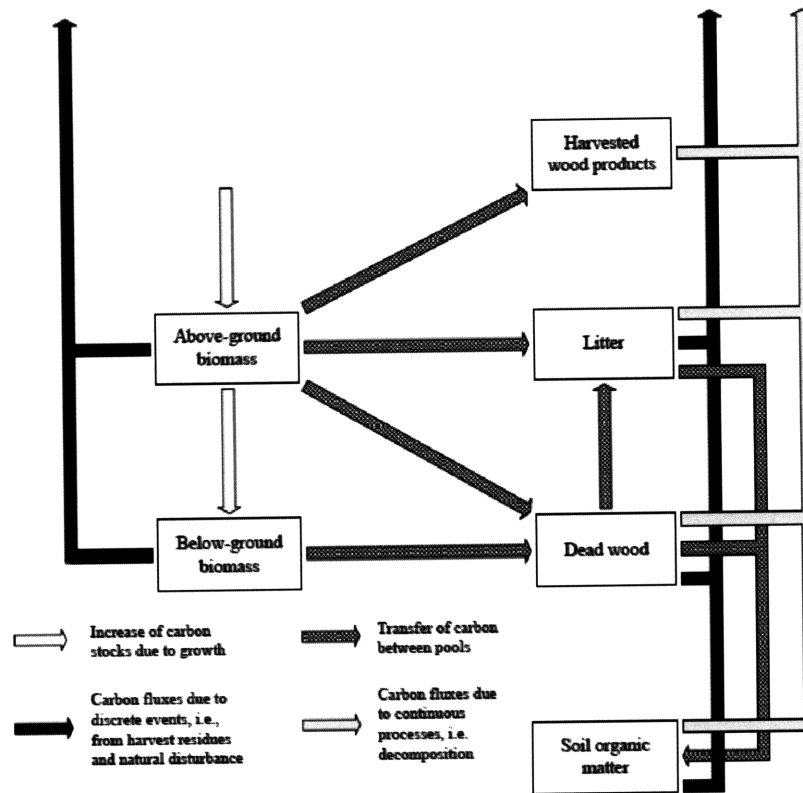
Figure 5-1 Carbon Cycle of Terrestrial Ecosystems (IPCC, 2006)

5.1.1. Project Impact

Chile possesses nearly one-third of the remaining large tracts of temperate forests with 15.6 million hectares of forest cover. The forests are 66% native, 13.5% plantations, and the remaining 0.5% classified as mixed forest. Chile contains almost every temperate forest type native to the Southern Hemisphere. The forests are important for climate regulation, flood control, water purification, and nutrient cycling. Forests in Chile are also important for biodiversity and are a source of timber and fuel wood for rural communities (Neira et al., 2002).

Chile is divided into fifteen regions. The dams are located in the Aysén Region (XI) and the natural gas plant is located in the Valparaiso Region (V), northwest of the metropolitan Santiago Region (RM) (Nation Master, 2005). The transmission line will run from Region XI north to Region V. The forest characteristics of these regions are shown in Figure 5-2, where dark green represents native forests.

For the dams, the percentage of disturbed forested land is known to be 31% (HidroAysén, 2008). Because the transmission line will travel through dense forests between Region XI and Region

V, it is assumed that 65% of the land is forested. Conversely, the land in the Valaparisa Region is primarily grassland and scrubland and it is estimated that only 10% of the land will be forest.[12]
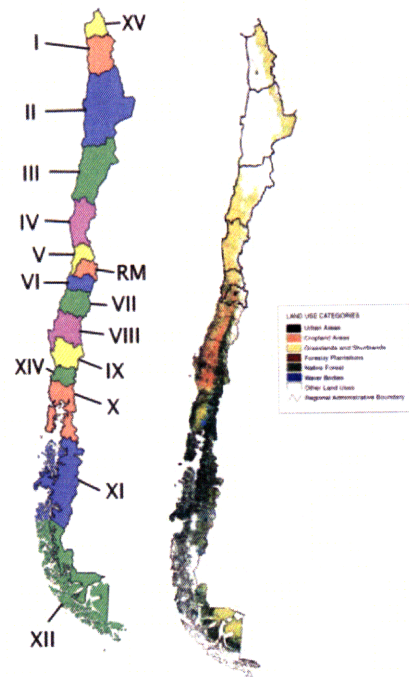
Figure 5-2 Forest Cover of Chile (Nation Master, 2005; Neira et al., 2002)[13]

Dams – the HidroAysén project will directly impact 8,950 ha of land, 31% of which is forest land. Therefore, deforestation of 2,730 ha will be a direct result of the dams, infrastructure, support facilities and the local transmission system (Figure 5-3 and Figure 5-4) (HidroAysén, 2008). The carbon impact of the dams results from two different mechanisms: flooding of the reservoir and clear cutting of the forests. Calculations assume that forested land is clear-cut prior to flooding, such that the entire 2,730 ha of impacted forests result in emissions as calculated in Section 5.1 Deforestation. Reservoir flooding calculations (Section 5.2 Reservoir Emissions) assume that flooded land is not standing forests. Based on these assumptions, there is no double counting of emissions.

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[12] Estimates are based on visual inspection of forest cover as shown in Figure 5-2.
[13] Black is urban, pink is cropland, yellow is grassland and scrubland, maroon is Forestry plantations, dark green is native forests, blue is water and white is other.
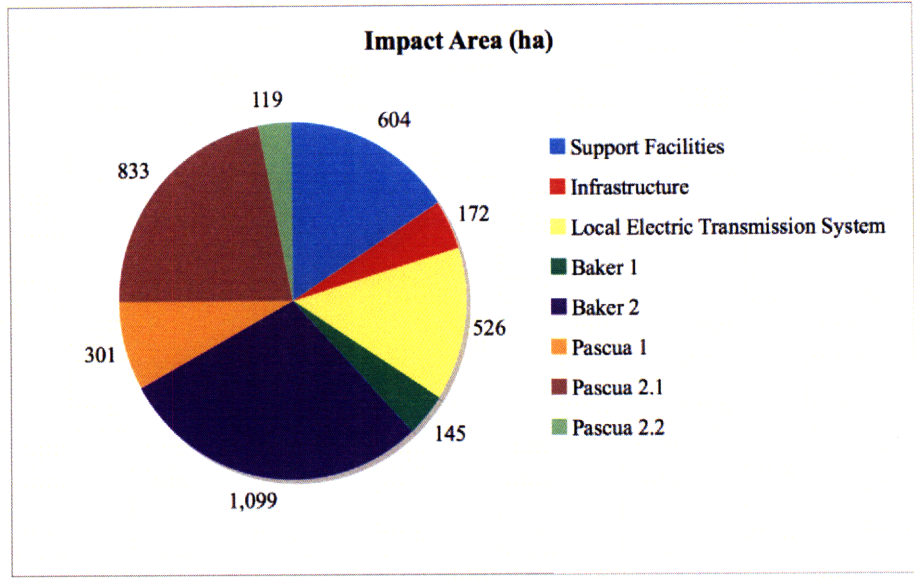
Figure 5-3 Land-Use Impact by Cause (HidroAysén, 2008)
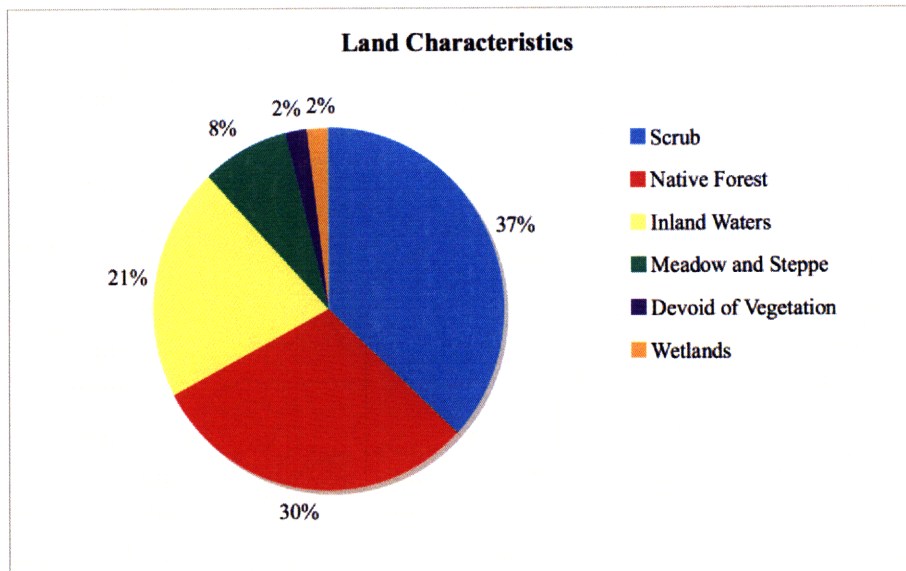
Figure 5-4 Current Use of Land Directly Impacted by the HidroAysén Project (HidroAysén, 2008, Table 4.6.1-5)

Transmission Line – the high voltage transmission line will travel 2,240 km connecting the Aysén and the SIC grids, and require a 70-m wide easement for construction and operation (Patagonia without Dams Campaign). As a result, 15,800 ha of land will be disturbed. It is estimated that 65% of the total impacted land, or 10,300 ha of the disturbed land is forest.

Natural Gas Plant – the natural gas plant will have a footprint of 65 ha based on a typical plant footprint of 0.02 ha/MW. This value is derived from the 300 MW plant with a 6 ha footprint found in the Ecoinvent System Processes database, accessed through SimaPro (PRé Consultants, 2009). It is estimated that 10% of the disturbed land (6.5 ha) is forest.

The area of impact of the dams, transmission line and natural gas alternative are summarized (Table 5-1).

Table 5-1 Summary of Deforested Area

Land Impact	Area of Influence (ha)		
	Dams	Transmission Line	Natural Gas
Forest	2,730	10,300	6.5
Total	8,949	15,800	65
% as Forest	31%	65%	10%

5.1.2. Chilean Forest Characteristics

Based on global maps depicting ecological zones and forest and land cover, Chile is made up of three primary ecological zones: subtropical mountain systems in the northern region, subtropical dry forest in the central region (Santiago) and temperate oceanic forest in the southern region (Aysén). With the exception of the Atacama dessert, Chile has a cool temperate moist climate (IPCC, 2006). Variables used to calculate the carbon impact of land-use change consistent with IPCC *Guidelines* are summarized in Table 5-2.

Based on ecological zone, the biomass characteristics of the impacted forests are calculated using global default values for above ground biomass (row 3, Table 5-2) and ratio of below ground to above ground biomass, R (row 6, Table 5-2):

$$B_{TOTAL} = B_{AboveGround} \times (1 + R) = B_{AboveGround} + B_{BelowGround}$$

For the dams requiring deforestation of temperate oceanic forests:

$$B_{TOTAL} = 180 \frac{tdm}{ha} \times (1 + 0.22) = 180 \frac{tdm}{ha} + 39.6 \frac{tdm}{ha} = 220 \frac{tdm}{ha}, \text{ where } tdm \text{ is tonnes dry matter}$$

It is assumed that the first half of the transmission line will travel through temperate oceanic forest and that the second half will travel through subtropical dry forest. Therefore, the variables used are an average of the two ecological zones.

36

Table 5-2 Variables for Calculating Land-use Impacts (adapted from IPCC, 2006)

Row	Variable Description	Units	HidroAysén Dams	Transmission Line	Natural Gas
1	Ecological Zone	-	Temperate Oceanic Forest	Temperate Oceanic Forest/Subtropical Dry Forest	Subtropical Dry Forest
2		-	South America	N/A	North and South America
3	Above Ground Biomass, $B_{AboveGround}$	tdm/ha	180	195	210
4	Above Ground Biomass, Range	tdm/ha	90 to 230	90 to 410	200 to 410
5	Tree Type	-	Conifers, Other Broadleaf	N/A	N/A
6	Ratio of Below Ground to Above Ground Biomass, R	-	0.22	0.23	0.24
7	Below Ground Biomass, $B_{BelowGround}$	tdm/ha	39.6	44.9	50.4
8	Total Biomass, B_{Total}	tdm	220	240	261
9	Above Ground net Biomass Growth in Natural Forests, G_W	tdm/ha/yr	5.65	4.83	4

5.1.3. Forest Land Converted to Grassland

It is assumed that after deforestation associated with development, that the land would be unmanaged and thus resort to a grassland state. Land converted from forest to grasslands involves the changes in carbon stock from biomass, dead organic matter, and soils (IPCC, 2006). The biomass and dead organic matter carbon stock changes are calculated for the deforestation associated with the dams, the transmission line and the natural gas baseline. Soil carbon stock changes are not calculated because a detailed soil classification of the area is not available.

Calculations assume that 100% of the carbon lost to the atmosphere is emitted as carbon dioxide. Carbon stock values are converted to CO_2 emissions by multiplying the carbon stock change by 44/12 based on the ratio of molecular weights.

Accounting for the conversion of forest to grassland requires a two-phase approach. In the first phase (first year) the abrupt ecosystem change causes the release of stored carbon, as carbon dioxide. In the second phase (years two to twenty), carbon stock changes are a result of the grassland system reaching equilibrium. However, using a Tier 1 approach, it is assumed that the grassland ecosystem will reach equilibrium in the first year, such that no stock exchanges occur after year one. Therefore, the only carbon fluxes considered are those that occur in the first year of disturbance.

Although land disturbance will occur over the life of the construction projects, it is assumed that it all occurs in the same year; because emissions are not weighted in time, land-use emissions simply contribute to the project total.

5.1.3.1 Biomass

The changes in biomass carbon stock are due to the removal of existing forest and the replacement with unmanaged grassland vegetation. In the first year of land-use change, it is assumed that all biomass in the forest ecosystem is released into the atmosphere immediately, such that residual biomass is zero. In other words, there is no transfer of forest biomass to the dead organic matter pool. It is also assumed that the grassland reaches equilibrium in the first year such that there are no emission fluxes due to land disturbance after the first year (IPCC, 2006).

Using the Tier 1 methodology, the change in biomass carbon stock is calculated (IPCC, 2006):

$$\Delta C_B = \Delta C_{CONVERSION} = (B_{BEFORE} - B_{AFTER}) \times \Delta A \times CF$$

where:

B_{AFTER} *is the residual biomass stock immediately after conversion, zero for Tier 1 estimates, tdm/ha*

ΔA *is the area of converted land, ha*

CF is the carbon fraction of dry matter, 0.50 tC/tdm

B_{BEFORE} *is the biomass stock of forests before conversion, or the B_{TOTAL} for the forests (Table 5-2, row 8) tdm/ha:*

$$B_{BEFORE} = B_{AboveGround} \times (1 + R)$$

where:

$B_{AboveGround}$ *is the total above ground biomass stock in the forests prior to land-use change, tdm/ha*

R is the ratio of below ground biomass to above ground biomass

This method is applied to the dams, transmission line and natural gas plant given the total deforested area. An example calculation for the dams (2,730 ha of converted forest land) is shown below and a summary of results can be found in Table 5-5.

$$\Delta C_B = (220 - 0) \frac{tdm}{ha} \times 2{,}730 ha \times 0.50 \frac{tC}{tdm} = 300{,}000 tC$$

Therefore, 300,000 tC or 1,100,000 tCO$_2$ (300,000 tC/yr × 44/12) is released from the forest biomass stock when land is converted to grassland.

38

5.1.3.2 Dead Organic Matter

The change in carbon stock from the dead organic matter pool can be estimated by looking at changes in the dead wood and litter pools (separately). However, this analysis only considers the changes in dead organic litter because dead wood default values are not available. For Tier 1 estimates it is assumed that all dead wood and litter is removed in the first year and that grasslands achieve steady state in the first year such that there are no emissions or removals after year one.

Using the Tier 1 methodology, the change in dead organic matter carbon stock is calculated as follows (IPCC, 2006):

$$\Delta C_{DOM} = \frac{(C_0 - C_n) \times A_{on}}{T_{on}}$$

Where:

ΔC_{DOM} is the annual change in carbon stocks of dead organic matter (litter), tC/yr

C_n is the litter stock as grassland, 0 tdm/ha for Tier 1 non-forest categories

C_0 is the litter stock as forest, 21 tdm/ha for mature forests (half broadleaf deciduous, half needleaf evergreen in cold temperate moist climates)

A_{on} is the area undergoing conversion from old to new land-use, ha

T_{on} is the time period to transition from old to new land-use category, default 1-year

This method is applied to the dams, transmission line and natural gas plant given the total deforested areas. An example calculation for the dams (2,730 ha of converted forest land) is shown below and a summary of results can be found in Table 5-5.

$$\Delta C_{DOM} = \frac{(21-0)\frac{tC}{ha} \times 2,730 ha}{1yr} = 57,300\frac{tC}{yr}$$

Because there are no carbon fluxes after year one, the ΔC_{DOM} of 57,300 tC/yr is the total carbon released from the project due to land-use change. This equates to 210,000 tCO_2 released from the dead organic matter pool as a result of deforestation

5.1.4. Loss of Carbon Sink

The loss of forests as a carbon sink is calculated by estimating the amount of carbon that would have accumulated in the forests, had they not been cleared for development. For a Tier 1 estimate, it is assumed that there are no changes in the dead organic matter carbon stock.

5.1.4.1 Biomass

Using the IPCC *Guidelines*, the loss of carbon sink is calculated as the carbon stock increase in biomass for undisturbed forests over time. For the purpose of these calculations it is assumed that no carbon is lost from wood removals, fuel wood, or disturbances and that the forests are left to grow naturally if the dam infrastructure project is not built. Therefore the change in carbon stock is just the change in above ground biomass from growth (IPCC, 2006):

$$\Delta C = \Delta C_G - \Delta C_L = \Delta C_G$$

$$\Delta C_G = A \times G_{TOTAL} \times CF$$

Where:

ΔC_G *is the annual increase in biomass carbon stock due to growth, tC/yr*

ΔC_L *is the annual loss in biomass carbon stock due to wood removals, fuel wood, or disturbances, assumed 0 tC/yr*

A is the area of land, ha

CF is the carbon fraction of dry matter, 0.50 tC/tdm

G_{TOTAL} *is the annual biomass growth, tdm/ha/yr*

$$G_{TOTAL} = G_W (1 + R)$$

G_W *is the annual above-ground biomass growth (Table 5-2, row 9), tdm/ha/yr*

R is the ratio of below ground biomass to above ground biomass

An example calculation for the dam project is provided:

$$\Delta C_G = 2,730 ha \times 6.89 \frac{tdm}{ha \bullet yr} \times 0.50 \frac{tC}{tdm} = 9,400 \frac{tC}{yr}$$

As a result of deforestation to build the dams, 9,400 tC/yr are (34,500 tCO_2/yr) are not sequestered annually. This can is considered as a net carbon emission to the atmosphere. Over a 25-year period, 863,000 tCO_2 can be attributed to the dam project.

5.2. Reservoir Emissions

The extent of greenhouse gas emissions that result from inundation of reservoirs is currently a large topic of research. The basic mechanism is the decomposition of organic matter resulting in the production of methane (CH_4) that can be released into the atmosphere (Figure 5-5) (Combs, 2008).
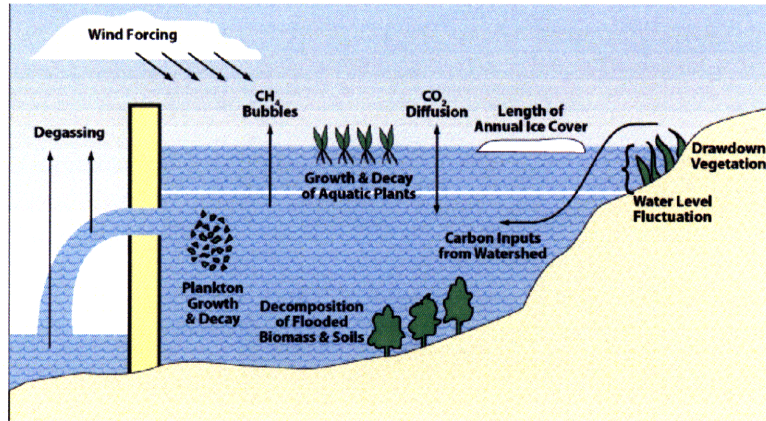
Figure 5-5: Factors affecting greenhouse gas emissions from reservoirs (Combs, 2008)

Carbon dioxide and methane emissions following the inundation of land can occur through three pathways: (1) diffusive emissions at the air-water interface; (2) bubble emissions that are released from sediment; and (3) degassing emissions due to sudden change in hydrostatic pressure. Degassing emissions can occur after flow through a turbine or a dam spillway. Carbon dioxide is primarily released through diffusive emissions and degassing is minor. However, methane emissions from bubbling and degassing can be significant; bubble emissions are particularly important in temperate and tropical regions (IPCC, 2006).

A study of Brazil's Turcuruí dam in the Amazonian rainforest looked at detailed mechanisms for methane release. Methane was released from several mechanisms including bubbles and diffusion emissions from the reservoir's surface, emissions from turbines that draw subsurface water into the intake, and emissions from the spillway. The discharge from the turbines results in the immediate release of degassed methane, or oxidation to carbon dioxide downstream of the dam. In Turcuruí the methane emitted through the turbines was 2 to 8 times greater than the release from bubbling and diffusion. Emissions from this tropical reservoir are significant contributing to 13-19% of the fossil fuel emissions from Brazil and are 1.3-1.9 times greater than the fossil fuel burned by São Paulo, Brazil's largest city (Fearnside, 2000).

Greenhouse gas emissions from reservoirs result from the release of nutrients, bacterial activity and decomposition of carbon. Studies of hydropower reservoirs at the La Grande complex in northern Quebec observed that the magnitude of carbon and methane emissions is a function of the reservoir water quality. Reservoirs with anoxic conditions favor methane emissions over carbon dioxide emissions. Currently, models cannot accurately predict GHG emissions from reservoirs, so in their absence, water quality models are used to determine the likelihood of anoxic conditions (Tremblay and Schetagne, 2006). Another indicator of methane emissions is the presence of macrophytes (floating weeds and water hyacinth, *Eichhornia crassipes*) on surface waters. Studies by Fearnside (1995) showed that areas of lakes with macrophytes had 3.25 times more methane emissions than open water.

5.2.1.1 Diffusive Emissions

The IPCC provides preliminary guidelines for estimating carbon dioxide and methane emissions from permanently flooded land. For estimating both CO_2 and CH_4, a Level 1[14] approach is used, which includes only contribution from diffusive emissions:

$CO2$ Emissions (tCO2/yr) = P × CO_2 Emission Factor (kg CO2/ha/day) ×Flooded Area (ha) ×f_A
$\times 10^{-3}$(tonne/kg)

$CH4$ Emissions (tCH4/yr) = P × CH_4 Emission Factor (kg CH4/ha/day) ×Flooded Area (ha) ×f_A
$\times 10^{-3}$ (tonne/kg)

Where:

P is Number of days without ice cover (days/yr)

Emission Factors are 15.2 kg CO2/ha/day and 0.061 kg CH4/ha/day (IPCC, 2006)

Flooded Area is the total reservoir surface area, including flooded land, lakes, and rivers (ha)

f_A is the fraction of the total reservoir area that was flooded within the last 10 years

Number of Days without Ice Cover, P

Lago Colonia, the lake closest to the Baker 2 dam site, freezes approximately three months each year (91 days, or 274 days without ice cover). Lago Bertrand and Lago Plomo, larger lakes in the area, do not freeze over (J. Leidich, personal communication, 2009). It is assumed that the dam reservoirs for Baker 1, Pascua 1, Pascua 2.1 and Pascua 2.2 will have a similar freeze cycle as Lago Colonia, because of their similar size, but the Baker 2 reservoir will not freeze over due to its large surface area (Table 5-3).

Table 5-3 Lake and Reservoir Seasonal Freezing

	Lake Surface Area (ha)	Time Un-Frozen (days/yr)
Lago Colonia	700	274
Lago Bertrand	9000	365
Lago Plomo	4500	365
Baker 1	710	274
Baker 2	3,600	365
Pascua 1	500	274
Pascua 2.1	990	274
Pascua 2.2	110	274

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[14] IPCC provides three levels (versus three tiers) for calculating the emissions from flooded land.

Percent Recently Flooded, f_A

Maps detailing the impact of the reservoir (Appendix B) are inspected visually to determine the area that is currently river, and the additional area that will be flooded by the construction of the dams. The fraction of the total reservoir that does not currently exist as river area, is considered newly flooded area. For the Baker 2 dam, f_A is 0.6 and for the remaining dams, given a total flooded area of 1,801 ha and a combined dam reservoir area of 2,310 the f_A is 0.78. The average fraction of newly flooded area for the dam system is 0.67 (Table 5-4).

Table 5-4 Fraction of Reservoir as Recently Flooded Land

	Dam Reservoir Area[15] (ha)	Percent of Reservoir that is Newly Flooded by Dams[16] (%)	Newly Flooded Area (ha)
Baker 2	3,600	**0.60**	2,160
Baker 1	710	0.95	675
Pascua 1	500	0.35	175
Pascua 2.1	990	0.95	941
Pascua 2.2	110	0.10	11
Total Freezing	2,310	**0.78**	1,801
Total	5,910	0.67	3,961

Calculations

Carbon dioxide emissions from reservoirs are observed in the first 10 to 15 years after flooding for boreal and tropical systems, after this time the reservoirs behave like natural lakes (Tremblay and Schetagne, 2006). The IPCC considers CO_2 emissions from reservoirs during the first ten years of flooding. The duration of methane emissions is unknown, but they are assumed to occur over the 25-year duration of the project. Based on the above assumptions and calculations inundation of the reservoir will result in 236,000 tCO_2e of emissions as shown:

Carbon Dioxide Emissions:

$$CO_2 Emissions = \left(\left(274 \frac{days}{yr} \times 2,310 ha \times 0.78 \right) + \left(365.25 \frac{days}{yr} \times 3,600 ha \times 0.60 \right) \right) \times$$

$$15.2 \frac{kgCO_2}{ha \bullet day} \times 10^{-3} \frac{tonne}{kg} = 19,500 \frac{tCO2}{yr}$$

Methane Emissions:

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[15] Adapted from HidroAysén, 2008; Ch. 1 Table 1.1-3
[16] Adapted from HidroAysén, 2008; Ch. 5 Figura 5.3.1-1, 2, 3, 4, 5; percent of area as existing river measured using visual inspection

$$CH_4 Emissions = \left(\left(274 \frac{days}{yr} \times 2{,}310 ha \times 0.78\right) + \left(365.25 \frac{days}{yr} \times 3{,}600 ha \times 0.60\right)\right) \times$$

$$0.061 \frac{kg CH_4}{ha \bullet day} \times 10^{-3} \frac{tonne}{kg} = 78.2 \frac{tCH_4}{yr}$$

Annual Reservoir Emissions (tCH₄ converted to tCO₂ using a GWP of 21, refer to Table 2-1):

$$AnnualEmissions = 19{,}500 \frac{tCO_2}{yr} + 78.2 \frac{tCH_4}{yr} \times 21 = 21{,}100 \frac{tCO_2 e}{yr}$$

Project Reservoir Emissions:

$$Total = 19{,}500 \frac{tCO_2}{yr} \times 10 yr + 78.2 \frac{tCH_4}{yr} \times 21 \times 25 yr = 236{,}000 tCO_2 e$$

5.3. Summary and Sensitivity

Emissions from land-use change are a result of the release of carbon stored in the ecosystem, the loss of carbon sink, and for the dams, the emissions from inundation of the reservoir (Table 5-5, Figure 5-6).

For the dams, 54% of emissions are a result of the release of carbon stock, 36% of the emissions are associated with the loss of carbon sink, and 10% of the emissions are from inundation of the reservoir. Of the reservoir emissions, 83% are emitted as carbon dioxide. In total, the dams contribute 1.8 million tonnes of carbon dioxide from land-use change.

The transmission line requires 1.8 times more deforestation than the dams, and results in four times the land-use emissions. The loss of carbon sink attributes 66% of the carbon emissions with the remaining 34% from the release of stored carbon. Of the stored carbon, 85% is from the carbon stored as biomass.

The land-use emissions associated with the natural gas plant are minimal; the dams and the transmission line emit 395 and 1330 times the emissions from the natural gas plant, respectively.

Table 5-5 Summary of Land-use Change Emissions

	Emissions (tCO2e)		
	HidroAysen Dams	**Transmission Line**	**Natural Gas**
Biomass	1,100,000	4,532,000	3,110
Dead Organic Matter	210,000	793,000	500
Release of Carbon Stock (Subtotal)	*1,310,000*	*5,325,000*	*3,610*
Loss of Carbon Sink	*863,000*	*2,795,000*	*2,500*
Released as Carbon Dioxide	195,000	0	0
Released as Methane	41,000	0	0
Reservoir GHG Emissions (Subtotal)	*236,000*	*0*	*0*
Total	*2,409,000*	*8,120,000*	*6,110*
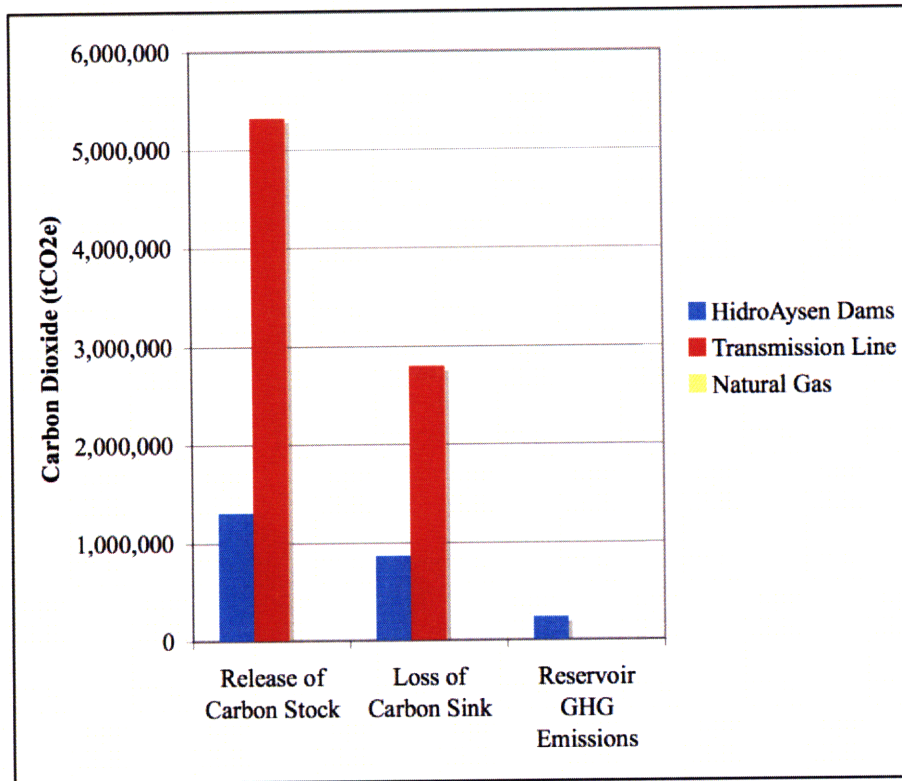
Figure 5-6 Summary of Land-use Change Emissions

5.3.1. Sensitivity of Deforestation Calculations

The largest source of error in the deforestation carbon emissions is the amount of forest area that is actually clear-cut. Although the area of impact is relatively well defined, the design and path of the transmission line has not been made publicly available, and therefore the land-use characteristics are unknown at this time.

The primary source of uncertainty resulting from the use of default biomass and growth factors, is that they are global values that do not reflect site specific conditions. In particular, parameters such as forest age, species composition and structure are unknown. For instance, the Food and Agriculture Organization estimates that the uncertainty in the growing stock is 30% for non-industrialized countries. To reduce uncertainty, the IPCC encourages countries to develop country or region specific biomass factors (IPCC, 2006).

5.3.2. Sensitivity of Reservoir Calculations

Default carbon dioxide emissions are based on aggregate data and do not account for site-specific conditions, as such, they are highly uncertain. The diffusive emission factor (15.2 kg CO_2/ha/day) is a global estimate for cold temperate moist climates, and is not specific to the Aysén region. This emission factor varies significantly from a minimum value 4.5 to a maximum value of 86.3 for the twenty reservoirs sampled. Additionally, in temperate regions CO_2 degassing is an important source that is not considered in these calculations (IPCC, 2006).

Default methane emissions are similarly variable and a global diffusive emission factor (0.061 kg CH_4/ha/day) for a cold temperate moist climate was used. The emission factors for the ten reservoirs studied range from 0.001 to 0.2. Because bubble and degassing emissions are significant for methane, the Level 1 approach used is an underestimate (IPCC, 2006).

In order to provide a more accurate estimate of carbon and methane emissions from flooded land, Chile should develop sampling strategies that account for temporal and spatial ecosystem variability. Future studies should use a Tier 3 approach that uses country specific data and estimates degassing emissions by measuring concentrations upstream and downstream of dams (IPCC, 2006).

6. OPERATION EMISSIONS

Operating emissions include emissions from the combustion of fuel and the transport of fuel to the power plant.

6.1. HidroAysén Project

During the operation of the dams, it is assumed that any operating energy required will come from hydropower resulting in no additional operating emissions. There are no emissions associated with energy supply because no fuel transport is required.

The five dams have a nameplate capacity of 2,750 MW and produced an annual average of 18,430 GWh; this translates into a capacity factor of 0.765:

Capacity Factor = Annual Electricity Output (GWh/yr)/Theoretical Output (GWh/yr)

$$CapacityFactor = \frac{18,430\frac{GWh}{year}}{24,100\frac{GWh}{year}} = 0.765$$

Where, the theoretical output is the amount of electricity generated if the plant had operated at nameplate capacity for the entire year:

$$TheoreticalOutput = 2,750MW \times 365.25\frac{days}{year} \times 24\frac{hours}{day} \times \frac{1}{1000}\frac{GW}{MW} = 24,100\frac{GWh}{year}$$

Hydropower is very efficient; new state of the art dams can reach efficiencies nearing 0.9, whereas older, or poorly serviced dams can have typical efficiencies of 0.6 to 0.8 (Tester et al., 2005).

The operating lifetime of the dams is not specified; Chilean dams have operated in excess of 50 years, although in some cases upgrades and replacement of equipment is required. The EIA considers the operation of the dams indefinitely and does not include plans for decommissioning.

6.2. Natural Gas Baseline

As detailed in Section 2.5 The Baseline Candidate: Natural Gas the baseline natural gas plant has a combined capacity of 3,270 MW to generate 17,200 GWh/yr. Natural gas is a fossil fuel found typical in underground reservoirs of porous rocks. Natural gas is 70 to 90% methane (CH_4) by volume with small portions of ethane, propane, butanes, hydrogen sulfide, nitrogen and carbon dioxide (Tester et al., 2005). Heat to work conversion is inefficient and thus the efficiency of fossil fuel combustion is typically low. Of the fossil fuels, natural gas burns the most efficiently, with a typical efficiency of 0.5 (Peterson, 2008). It is assumed that a modern natural gas plant with normal maintenance can operated for 25 years (J.W. Tester, personal communication, 2009).

In 2006, Chile consumed 292,251 TJ of natural gas emitting 14.7 million tonnes of carbon dioxide (EIA, 2006). This corresponds to a natural gas emissions factor for Chile of 50,300 kg CO_2/TJ (0.0000503 tCO_2/MJ) natural gas burned, 22% lower than the default emission factor (64,200 kg CO_2/TJ) provided in the IPCC *Guidelines* (IPCC, 2006).

6.2.1. Combustion

Carbon dioxide emissions from the burning of natural gas in Chile were calculated using the Tier 2 approach for stationary combustion outlined in the IPCC *Guidelines*. The resulting emissions are approximately 6.24 million tCO_2 annually or a total of 156 million tonnes over a 25-year operating period.

Project Emissions (tCO₂) =Annual Emissions (tCO₂/yr) × Operation Duration (yr)

$$\mathrm{Pr}\,ojectEmissions = 6,240,000 \frac{tCO_2}{yr} \times 25\,yr = 156,000,000 tCO_2$$

Annual Emissions (tCO₂/yr) =Fuel Consumption (TJ/yr) × Emission Factor (kg CO₂/TJ)/ × 10⁻³ (tonne/kg)

$$AnnualEmissions = 124,000 \frac{TJ}{yr} \times 50,300 \frac{kgCO_2}{TJ} \times 10^{-3} \frac{tonne}{kg} = 6,240,000 tCO_2$$

Fuel Consumption (TJₜ/yr) =Plant Capacity(MJₑ/s) × 1/η × CF× 86,400 (s/day)× 365.25 (day/yr) × 10⁻⁶ (TJ/MJ)

$$FuelConsumption = 3,270 \frac{MJ_e}{s} \times \frac{1}{0.5} \times 0.6 \times 86,400 \frac{s}{day} \times 365.25 \frac{day}{yr} \times 10^{-6} \frac{TJ}{MJ} = 124,000 \frac{TJ_t}{yr}$$

Note, the efficiency of a power plant is a measure of the effectiveness of converting thermal energy as natural gas into electricity:

η = energy output as electricity (MJₑ) /energy input as fuel (MJₜ)

Where a megajoule (MJ) is the measure of energy: the subscript "e" is for electrical energy, and the subscript "t" is for thermal energy.

6.2.2. Natural Gas Transport

In order to transport natural gas it is cooled to below -160°C where it is in a liquid state known as liquefied natural gas (LNG). In 2006 there were 17 terminals worldwide where LNG is liquefied and pumped onto LNG ships and approximately 40 terminals that received LNG tankers (GlobalSecurity.org, 2009). LNG tankers are typically spherical or box-shaped and run by steam turbines driven by diesel motors. Based on the world LNG tanker fleet and capacity,

the average ship holds 124 million liters of liquefied natural gas[17] (Penwell Corporation, 2009); this is equivalent to 2,890 TJ of natural gas based on the energy density of LNG (1.5 MPa) of 23 MJ/L (MIT Energy Club, 2007).

Based on an annual fuel consumption of 124,000 TJ to power the 3,270 MW plant, roughly 43 tanker deliveries will be required annually. Natural gas will be supplied through a LNG terminal currently under construction northwest of Santiago. It is most likely that LNG will come from Trinidad and Tobago or LNG terminals in Africa such as Egypt, Libya, or Nigeria (J. Leidich, personal communication, 2009). Assuming LNG travels from Trinidad and Tobago, and that the ship will have to travel around South America (versus through the Panama Canal), it will take approximately 20 days (40 days roundtrip) for the delivery of LNG (J. Golenbock, personal communication, 2009). Following IPCC *Guidelines*, a Tier 1 method for calculating water-borne navigation emissions is used. Given an emission factor for diesel fuel of 74,100 kg CO_2/TJ and an average consumption of a liquid bulk carrier of 41.8 tonnes fuel/day (IPCC, 2006), the tanker emissions are calculated:

Project Emissions (tCO2) = Annual Emissions (tCO₂/yr) × Operation Duration (yr)

$$TotalEmisisons = 228,000 \frac{tCO_2}{yr} \times 25 yr = 5,700,000 tCO_2$$

Annual Emissions (tCO₂/yr) = Fuel Consumed (TJ/yr) × Emission Factor (kg CO₂/TJ) × 10⁻³ (tonne/kg)

$$AnnualEmisisons = 3,080 \frac{TJ}{yr} \times 74,100 \frac{kgCO_2}{TJ} \times 10^{-3} \frac{tonne}{kg} = 228,000 \frac{tCO_2}{yr}$$

Fuel Consumed (TJ/yr) = Num. Trips (trips/yr) × Trip Time (days) × Ave. Fuel Consumption (kg fuel/day) × Energy Density of fuel (TJ/kg)

$$FuelConsumed = 43 \frac{trips}{yr} \times 40 \frac{days}{trip} \times 41.8 \frac{tonne_{fuel}}{day} \times 42.8 \frac{MJ}{kg} \times 10^3 \frac{kg}{tonne} \times 10^{-6} \frac{TJ}{MJ} = 3,080 \frac{TJ}{yr}$$

The result is a consumption of 3,080 TJ of energy consumed in the transport of natural gas attributing 5.7 million tonnes of carbon dioxide over the 25-year lifetime of the project.

6.3. Summary and Sensitivity

The combustion of natural gas over the 25-year operating life of the natural gas plants contributes to 96% of the operation emissions. The remaining 4% is from the transport of natural gas as LNG. In total 161.7 million tonnes of carbon dioxide emissions result from the operation of a 3,270 MW natural gas facility (Table 6-1).

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[17] Based on a total fleet of 257 ships and a total capacity of 31.9 billion liters.

Table 6-1 Summary of Operation Emissions

Emissions Source	Emissions (tCO2e)	
	HidroAysén Dams	Natural Gas
Combustion	0	156,000,000
Fuel Imports	0	5,700,000
Total	*0*	*161,700,000*

The efficiency and capacity factor of the natural gas plant are based on typical values – the actual values are dependent on the facility specifications. Because combustion emissions represent 96% of the operation emissions, any refinement in efficiency and capacity factor at the plant could provide significant improvement in accuracy to the operation emissions calculations. It is recommended that information about the operation of existing Chilean natural gas plants be used to refine the combustion operation emissions for natural gas.

There is significant uncertainty surrounding the shipment frequency, source of natural gas, and the general navigation transport emissions. However, they only represent 4% of the natural gas operation emissions and therefore refinement in these numbers will only have a minimal impact.

7. RESULTS

Emissions from construction, land-use, materials, and operation of the dams, the high voltage transmission line, and a natural gas alternative are calculated (Table 7-1). The emissions from the natural gas baseline are 13 times more than those associated with the dams and transmission line combined. Ninety-six percent of the emissions from natural gas are associated with the combustion of fossil fuels for 25-years.

Table 7-1 Summary of Project Emissions

	Emissions (tCO2e)		
	HidroAysén Dams	Transmission Line	Natural Gas
1. Construction			
Construction Equipment and Machinery	872,000	0	209,000
Bus Transport of Personnel	6,370	0	12,400
Aviation Transport of Personnel	36,800	0	0
Construction Subtotal	*915,170*	*0*	*221,400*
2. Land Use			
Release of Carbon Stock	1,310,000	5,325,000	3,610
Loss of Carbon Sink	863,000	2,795,000	2,500
Reservoir Emissions	236,000	0	0
Land-use Subtotal	*2,409,000*	*8,120,000*	*6,110*
3. Materials			
Embedded Energy of Materials	446,000	839,000	39,300
Materials Subtotal	*446,000*	*839,000*	*39,300*
4. Operation			
Combustion	0	0	156,000,000
Fuel Imports	0	0	5,700,000
Operation Subtotal	*0*	*0*	*161,700,000*
TOTAL	*3,770,170*	*8,959,000*	*161,966,810*

The biggest impact for the dams is the emissions associated with land-use change (Figure 7-1), contributing to 64% of the emissions. During construction, equipment and machinery contribute 23% of the dam emissions and the transport of personnel contributes only 1% of the dam emissions. The embedded energy of materials, primarily from concrete, contributes 12% of the dam emissions.

The transmission line emissions are primarily from land-use change impacts (91%) with the remaining impact associated with the embedded energy of materials. Total transmission line emissions are 2.4 times more than the emissions associated with the HidroAysén dam project. Therefore, the hydropower project would have a significantly smaller impact if the transmission line weren't needed.
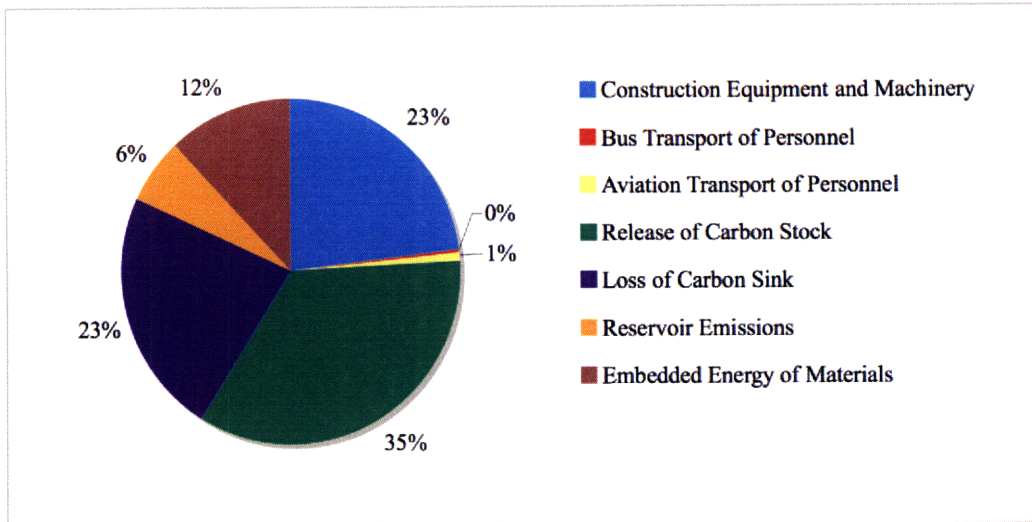
Figure 7-1 Carbon Impact of Dams by Category

7.1. Sensitivity

The largest uncertainty is the lack of definition of project design due to a lack of accessible data on the dam project and an unclear definition of the design of the transmission line and the natural gas plant. This analysis could be revised given more accurate and country-specific information for each project component. Because this analysis would have benefited from direct cooperation with the project team, it is recommended that CONAMA require a greenhouse gas analysis be included in the environmental impact assessment process.

Additionally, the life span of a natural gas plant is likely half that of a dams' operating life. Although the dam lifetime was considered 25-years for comparison purposes, if the dams are productive for 50 years, two natural gas plants would be required to produce the same energy, thereby doubling the impact of the natural gas alternative.

Despite uncertainty in each area, the analysis provides valuable insight on the impact of a dam project and the value of citing a dam close to the demand center.

8. IMPLICATIONS AND CONSIDERATIONS

The findings of this study indicate that hydropower projects are not carbon neutral. The consequence of land-use change and development in rural areas can be significant and should not be overlooked. The impact from large infrastructure construction and material embedded energy are also important carbon considerations.

Although this study indicates that natural gas power emits 13 times more carbon dioxide emissions than the proposed dams, this does not imply that the hydropower dams are the best option. The sustainability of the whole dam project is not assessed, and it is recommended that additional factors be considered including social, economic, and environmental consequences for Aysén region and for Chile as a whole. For instance, the deforestation of Chilean forests carries a much greater significance than just carbon emissions, including permanent alteration of habitats and potential extinction of key species.

A qualitative discussion about the sustainability of hydropower and the potential for alternatives is presented herein.

8.1. Sustainability of Hydropower

Hydropower is the most significant global renewable energy source today providing 16% of the world's electricity production (IHA, 2005). More than half of the global hydropower capacity comes from the United States, Brazil, Canada, China, and Russia. It is expected that South America's hydropower capacity will increase by a factor of two (WEC, 2008). At the global scale, 2002 levels of hydropower generation offset 4.4 million barrels of oil-equivalent (thermal electric generation) a day, roughly 6% of the world's oil production (WCD, 2002).

However, conventional hydro projects have significant impacts on water resources; although hydroelectric plants do not consume water (with the exception of evaporation from the reservoir), they do alter the upstream and downstream ecosystems. The World Resource Institute estimated that large dams modify 46% of the world's primary watersheds. Global freshwater storage capacity is decreasing at a rate of one percent per year due to sedimentation in reservoirs. As a result, it is estimated that 25% of the global storage capacity will be lost in the next several decades (WCD, 2002).

Water extraction from rivers and lakes has been growing as a result of increased population and wealth. As water demands increase so will the challenges surrounding water availability for all purposes including hydropower. Climate change impacts have the potential to further complicate the water balance; studies performed by the IPCC indicate increased variability of weather and seasonal distribution of water. Additionally, the world's watersheds are home to 40% of the fish species; of these fish, 20% have become threatened, endangered or extinct in the last few decades as a result of watershed manipulation, including withdrawals and alterations to natural rivers and streams (WCD, 2002).

The social consequences of dams can be both positive and negative. Large infrastructure projects provide jobs, affordable electricity, flood control, irrigation and recreation among other attributes. Between 1972 and 1996, floods affected 65 million people, more than any other type of disaster including war, drought or famine, and dams have helped alleviate disasters from

53

floods. Conversely, large dams are also responsible for the displacement of 40 to 80 million people worldwide (WCD, 2002).

Barriers to waterpower development in Chile include: poorly defined and managed water rights, easements and access to technical data; inadequate management strategies for promotion of projects that combine hydropower for irrigation and generation; and concerns about direct benefits to communities local to proposed dam sites (Universidad de Chile, 2008). These challenges were not addressed as part of this study, nor were considerations such as the disturbance to ecosystems, reduction in water storage capacity, evaporative losses, or the benefits from flood control, recreation and irrigation. A full sustainability assessment of the five proposed dams in Chilean Patagonia is recommended and should consider all of the consequences and benefits of hydropower.

Additionally, maximizing power from existing hydroelectric facilities and adding hydropower to existing dams could add capacity without building new, socially and environmentally controversial impoundment dams. Harnessing run-of-river power on the small scale has proven successful in the Aysén region, and can have a positive contribution with significantly less environmental impact.

8.2. Alternatives

Although this analysis does not quantitatively consider alternatives such as geothermal, solar or wind power, it defines a method for future analysis. These options should be considered explicitly as an alternative to the proposed dam project.

A 2008 study completed by the Universidad de Chile and Universidad Técnica Federico Santa María, estimated the potential contribution (defined using several parameters such as cost of generating energy, distance from project to consumption, and degree of penetration) of energy efficiency and renewable energy in Chile between 2008 and 2025. The study projected the adoption of energy efficient technologies and the potential for renewable technology for low (conservative), medium (dynamic), and high (dynamic-plus) adoption scenarios (Universidad de Chile, 2008).

The study estimated that in 2025, the SIC will have an expected demand of 105,560 GWh, and that reductions from energy efficient measures could replace 10 to 23% of this demand. This is an annual reduction in capacity requirements ranging from of 1,754 MW to 4,121 MW or 10,500 to 24,650 GWh/yr. In other words, *the need for 2,750 MW (18,430 GWh/yr) of electricity could be eliminated through energy efficiency measures.* However, a widespread adoption of energy efficient technologies requires strong public polices to reach the reduction levels estimated (Universidad de Chile, 2008).

The study also estimated that renewables have the potential to generate between 16 and 28% of Chile's 2025 demand. The economically feasible installed renewables by 2025 ranges from 3,330 MW to 5,750 MW or 17,740 GWh/yr to 29,700 GWh/yr. In other words, *the need for 2,750 MW (18,430 GWh/yr) of electricity could be eliminated through development of economically feasible renewable energy installations.* Chile has already demonstrated its commitment to renewable energy by passing a law to produce 5% electricity from renewable

54

sources for all energy contracts signed after 2010; however, institutional and regulatory barriers to adoption of these technologies still remain a significant obstacle (Universidad de Chile, 2008).

When considering the renewable energy options for Chile, it is likely that a combination of energy efficiency measures and renewable energy systems will be required to ensure energy security and to deliver the growing energy demands. The estimated technically feasible generation capacity by technology (Figure 8-1) shows that both small hydropower and geothermal will be large players in Chile's energy sector by 2025. Although there is no current geothermal resource developed in Chile, the estimated growth is the largest among the renewable options, testament to the countries significant geothermal resources. Solar thermal and solar PV are expected to grow very slowly, a steady increase in wind power and a rise and then fall of biomass power are also projected (Universidad de Chile, 2008).

Although in the dynamic scenario, geothermal capacity is less than the estimated hydropower capacity, this is sensitive to the scenario assumptions; the dynamic plus scenario suggests that geothermal may match or surpass hydropower capacity in 2025. Additionally, while it looks like hydropower in 2025 is beginning to level off, geothermal power generation is still growing rapidly (Universidad de Chile, 2008).
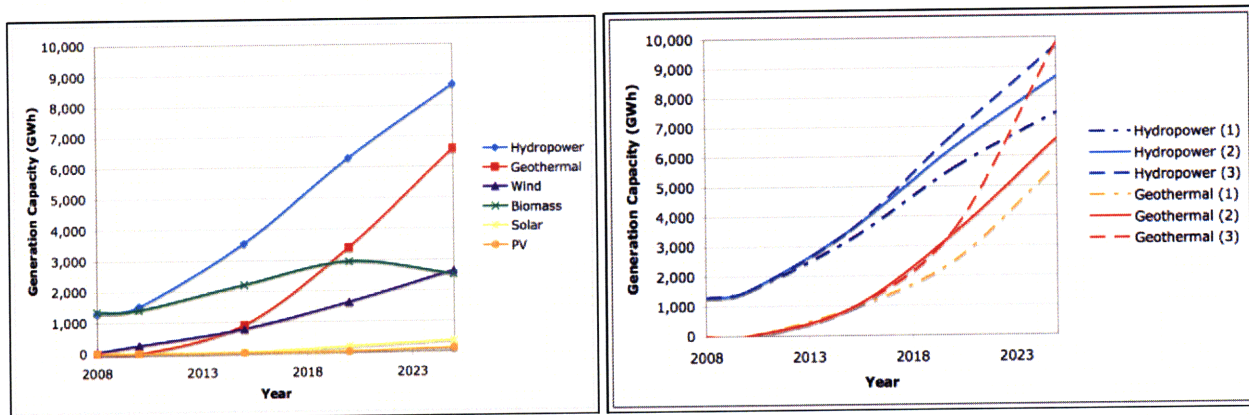

Figure 8-1 Estimated Generation Capacity (2008 to 2025): Renewable technologies for dynamic scenario; Hydropower and geothermal for (1) conservative (2) dynamic (3) dynamic-plus scenario (adapted from Universidad de Chile, 2008)

8.2.1. Geothermal in Chile

Chile has one of the largest undeveloped geothermal global resources due to the volcanic activity controlled by the convergence of the Nazca and South-America plates (Sepúlveda et al., 2005). Geothermal exploration in Chile began in 1968 and includes geological, geochemical and volcanological surveys covering much of southern Chile. Wells were also drilled in El Tato and Puchuldiza. From these studies it is estimated that Chile has several thousands megawatts of domestic geothermal resources. In 2000, the government enacted the Geothermal Law that regulates exploration and exploitation of geothermal resources (Ehrlich, 2008). Based on exploration of areas such as El Tatio and Puchuldiza, approximately 16,000 MW for 50 years could be exploited with fluid temperatures over 150°C (302°F) at depths less than 3,000 m (1.9 mi) (Lahsen et al., 2005).

A collaborative effort between Fundación Chile and Pacific Geothermal to explore, exploit, and operate geothermal fields has begun, but no geothermal power plant exists in Chile today. This initiative is expected to have a major impact on Chile's energy industry providing a mechanism for energy independence (Fundación Chile, 2006). In April 2008 Chile's national oil company, Empresa Nacional del Petróleo (ENAP), began a joint venture with Antofagasta Minerals, a London-based copper mining group. The team plans to develop 400 MW of geothermal capacity in Chile over the next ten years (Ehrlich, 2008).

Because geothermal plants can provide base-load power, geothermal energy has a competitive advantage over intermittent wind and solar power; the capacity factor of a geothermal plant is up to 95%, which is on par with fossil fuel power plants. Figure 8-2 shows how geothermal and hydropower compare to other renewable energy technologies in terms of capacity factor and price per kWh. Geothermal and hydropower not only have high capacity factors but also have low costs that are competitive with fossil fuel prices (before subsidies); the average retail price of electricity is 10¢/kWh (EERE, 2008).

Because of the available resource in Chile and the potential for inexpensive base-load power, geothermal is an obvious choice as an alternative to developing hydropower in the Aysén region. *It is estimated that 30-50% of the proposed 18,430 GWh/yr proposed dam project could be offset by geothermal power.* However, significant barriers to geothermal energy in Chile must be overcome; barriers include: high capital investment for the exploration of geothermal resource; uncertainty of resource and associated financial risk; inadequate existing infrastructure; and institutional and regulatory limitations (Universidad de Chile, 2008).
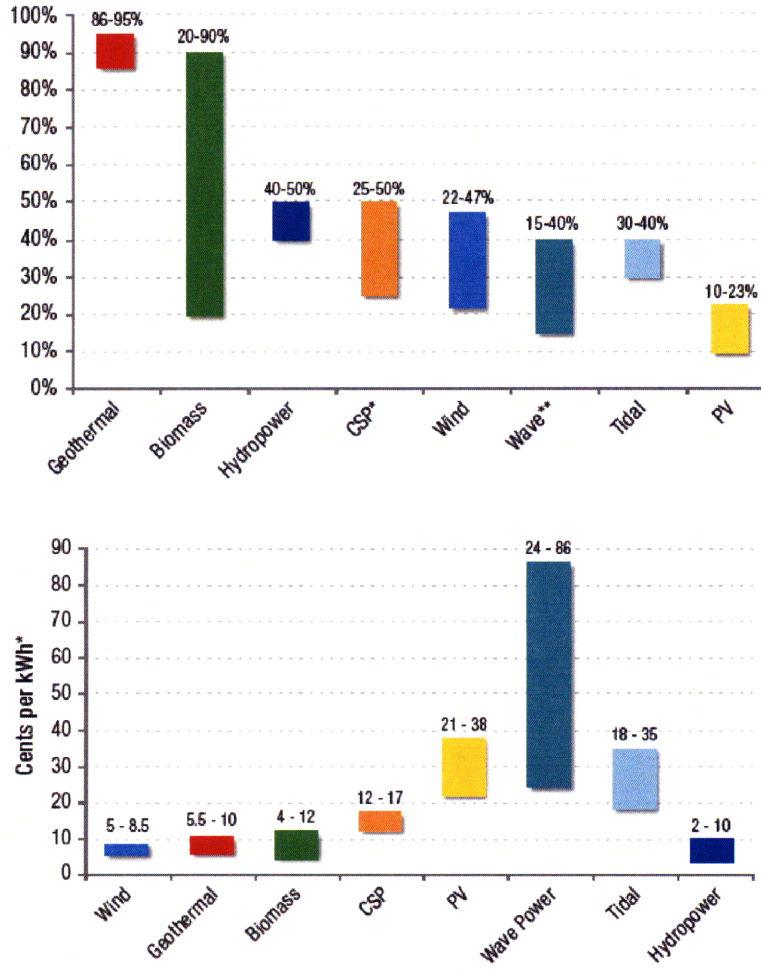
Figure 8-2 Renewable Energy Technology Capacity Factors and 2007 Price in USD (EERE, 2008)

9. CONCLUSIONS

A carbon impact assessment is used to quantify the impact of the proposed hydroelectric dams in Chilean Patagonia. This method identifies key emission sources for the dams that often are not included in the big dam debate. The value provided is the order of magnitude relationships between the emission categories, and between the dams and transmission line system and the natural gas alternative. For the project in the Aysén region, the rural location, and thus the need for a high voltage transmission line, is 70% of the carbon problem. Therefore, development closer to the source will reduce the need for extensive deforestation and the associated carbon consequences. Additionally, this study only looks at one aspect of sustainability, and a full sustainability assessment that considers the breath of social, economic and environmental issues is recommended.

Although natural gas emits 13 times more carbon dioxide than the dam project, the other consequences of using natural gas, a non-renewable fossil fuel, are not factored into the analysis. Although natural gas is the most likely alternative, it does not mean it is the most sustainable alternative. Studies have shown that energy efficiency and renewable energy options are economically feasible for Chile, and these options should be emphasized and explored further. If Chile is to grow a low-carbon economy, options for supplying base load dispatchable electricity will be needed. To address this need, Chile should develop a multi-tiered approach that combines energy efficiency with renewable energy technologies such as geothermal, solar thermal, wind and small hydro.

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APPENDIX B. SUPPORTING FIGURES AND MAPS

The figures and maps presented in this section were used to derive inputs required to calculate the carbon emissions associated with the HidroAysén dam project.
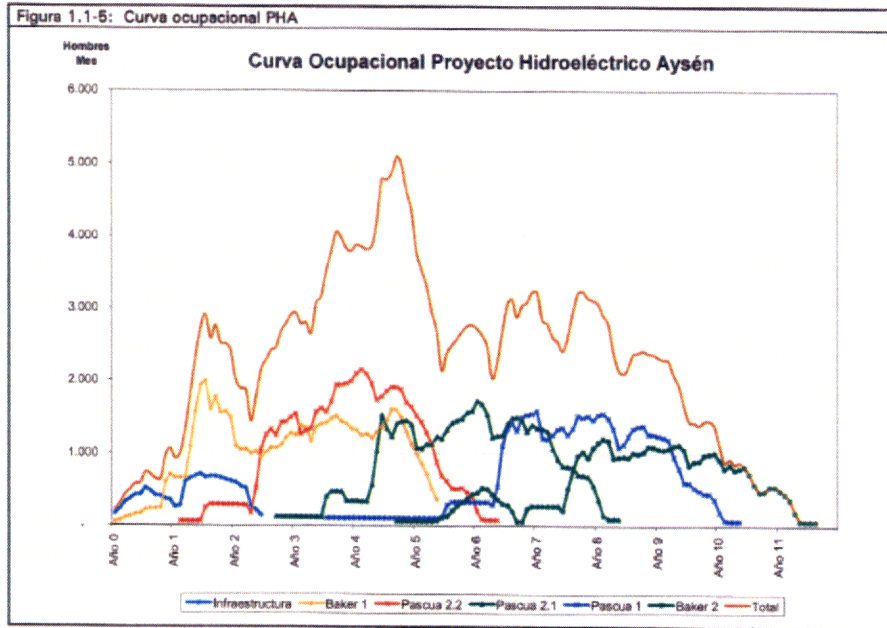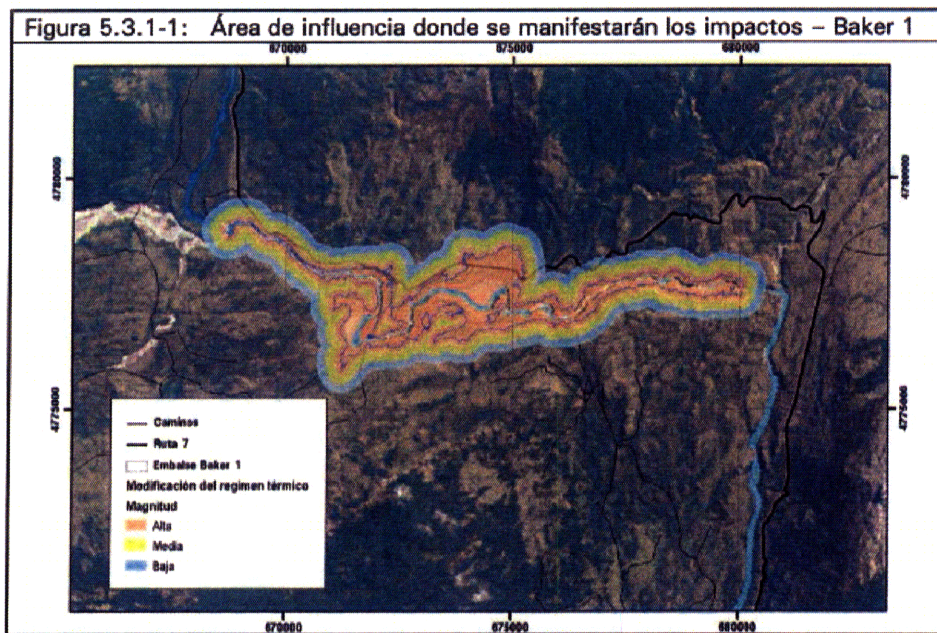

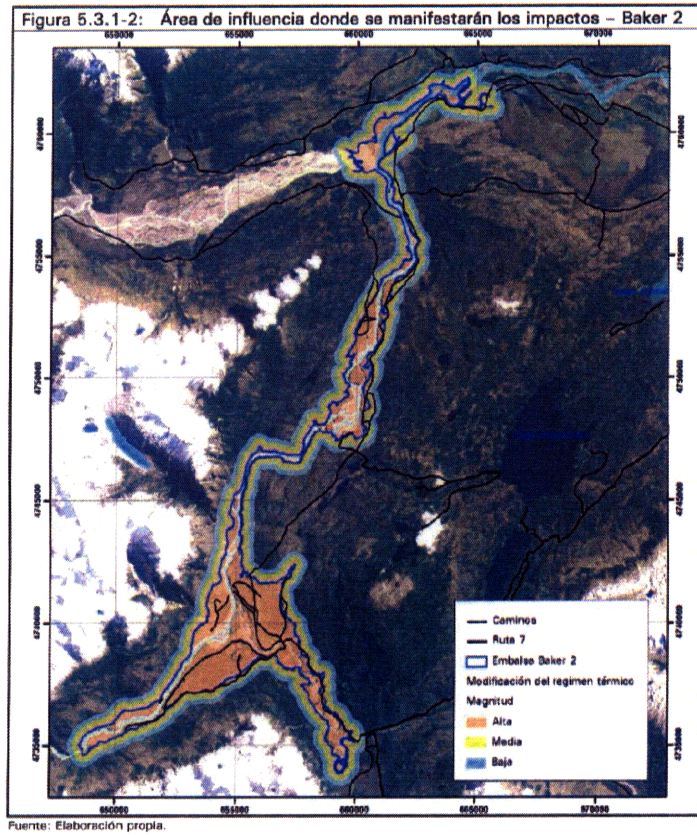**Figure B-1: Dam Project Workforce over 12-year Construction Period (HidroAysén, 2008)**

Figure B-2 Baker 1 Reservoir and Area of Influence (HidroAysén, 2008)

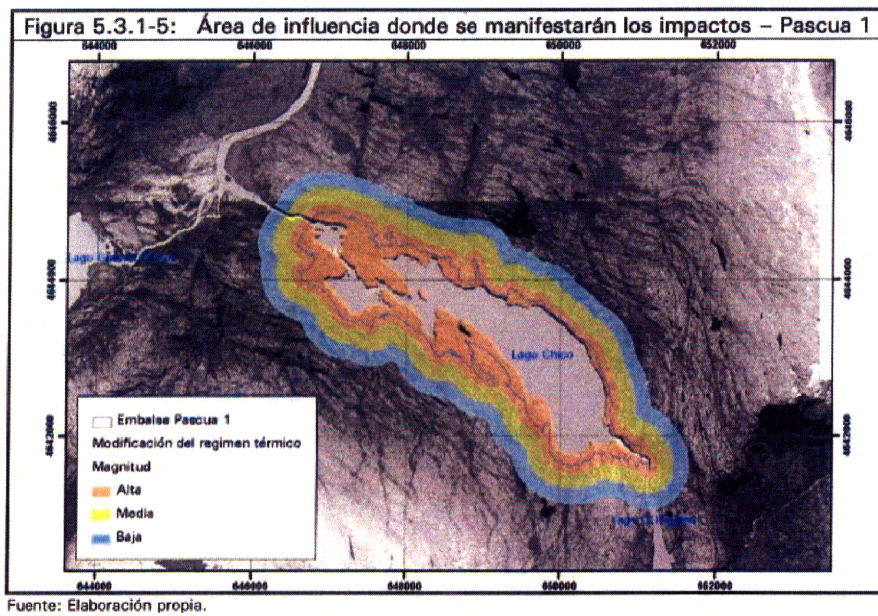**Figure B-3 Baker 2 Reservoir and Area of Influence (HidroAysén, 2008)**

Figure B-4 Pascua 1 Reservoir and Area of Influence (HidroAysén, 2008)
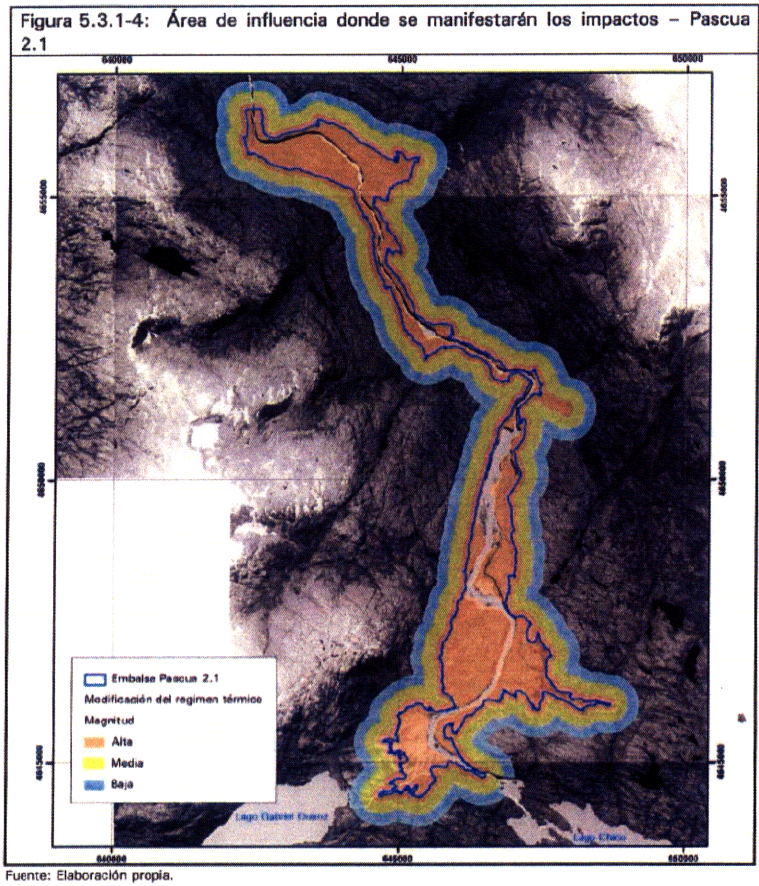
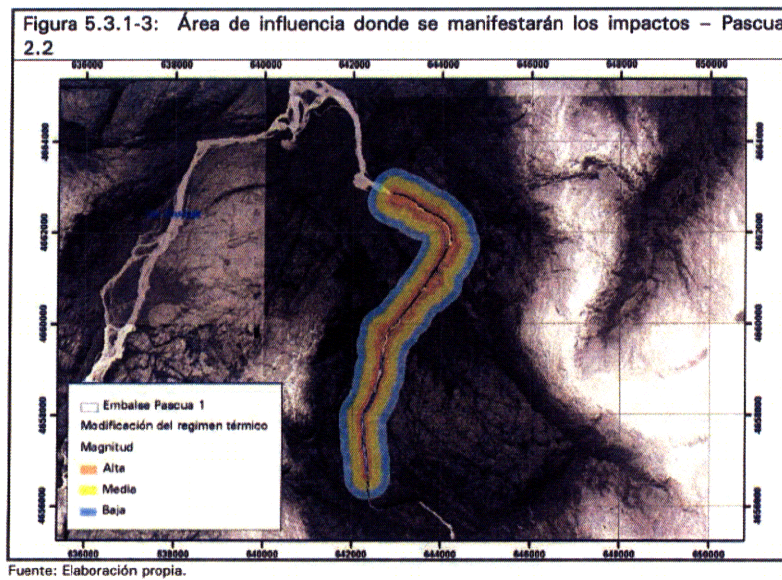Figure B-5 Pascua 2.1 Reservoir and Area of Influence (HidroAysén, 2008)

Figure B-6 Pascua 2.2 Reservoir and Area of Influence (HidroAysén, 2008)